



A Multiwavelength View of the First Type Ic-BL Supernova with an Einstein Probe X-Ray Shock Breakout

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Abstract

In 2026 March, the Einstein Probe (EP) discovered its nearest ($z = 0.0343$) Fast X-ray Transient (FXT), EP 260321a, the first EP FXT to provide a strong match to expectations for X-ray “shock breakout” (SBO) emission. Here, we present our multiwavelength follow-up campaign of EP 260321a and its broad-line Type Ic (Ic-BL) supernova (SN) counterpart, SN 2026gzf. We show that our radio follow-up extending over 5.8–54.5 days post-FXT rules out an on-axis jet counterpart of isotropic-equivalent kinetic energy $E_K \gtrsim 10^{49}$ erg for circumburst densities $n > 10^{-2} \text{ cm}^{-3}$ and assuming microphysical parameters $\epsilon_e = \epsilon_B = 0.1$. Our radio data also constrain a median mass-loss rate of $\dot{M} \lesssim 1.2 \times 10^{-5} M_\odot \text{ yr}^{-1}$ for a Wolf–Rayet progenitor. In addition, we derive SN 2026gzf’s properties, including ^{56}Ni mass, diffusion timescale, and expansion velocities, from our $\sim$ nightly cadence optical data and compare them with those of optically discovered Type Ic-BL SNe, finding that

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SN 2026gzf is well within the 90% confidence interval across all properties. We further fit SN 2026gzf's light curve and determine that combined emission from both interaction with CSM and ^{56}Ni radioactive decay provides the best fit with plausible model parameters. Finally, using the rate of Ic-BL SNe from the Zwicky Transient Facility Bright Transient Survey and assuming all Type Ic-BL SNe produce EP 260321a-like FXTs, we infer an expected rate of EP-detected SBOs of $4.4\text{--}16\text{ yr}^{-1}$. This is inconsistent at the 90% confidence level with current EP detection rates, potentially indicating that most Type Ic-BL SNe produce less luminous X-ray SBO signals compared to EP 260321a.

Unified Astronomy Thesaurus concepts: [Supernovae \(1668\)](#); [Core-collapse supernovae \(304\)](#); [Wolf-Rayet stars \(1806\)](#); [Gamma-ray bursts \(629\)](#)

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1. Introduction

The earliest electromagnetic (EM) radiation from core-collapse supernova (SN) explosions is the shock breakout (SBO; e.g., S. A. Colgate 1974; S. W. Falk 1978; R. I. Klein & R. A. Chevalier 1978; V. S. Imshennik et al. 1981; L. Ensmann & A. Burrows 1992; C. D. Matzner & C. F. McKee 1999; E. Nakar & R. Sari 2010; E. Waxman & B. Katz 2017). SBO occurs when the radiation-dominated SN explosion shock crosses the surface of an evolved star, or when the optical depth (τ) ahead of the shock drops below $\tau < c/v_s$, where v_s is the shock speed. This SBO releases a bright flash that shines at X-ray or UV wavelengths and persists over seconds to $\sim$ hour timescales (E. Waxman & B. Katz 2017). As the earliest EM signatures of SN explosions, SBOs are direct probes of the very early stages of the core-collapse process, providing critical insight into the progenitor star mass and composition, explosion time, and rate of mass loss prior to explosion.

Despite their potential as probes of the preexplosion environment, SBOs are rarely detected as they require observations of the SN at nearly exactly the time of explosion. Though wide-field optical surveys have dramatically increased the rate of SN discoveries (e.g., N. M. Law et al. 2009; C. S. Kochanek et al. 2017; J. L. Tonry et al. 2018; E. C. Bellm et al. 2019), SBOs are expected to peak at temperatures ~ 0.1 keV (E. Nakar & R. Sari 2010) and are not expected to produce optical emission during the breakout phase. Therefore, wide-field UV and soft X-ray detectors provide the only avenue to discover SBOs from a systematic perspective.

Prior to 2024, a number of fast X-ray transients (FXTs) had been discovered by soft X-ray satellites such as HETE-2, Beppo-Sax, and MAXI (J. Heise et al. 2001; T. Sakamoto et al. 2005; A. M. Soderberg et al. 2005; M. Matsuoka et al. 2009) or in archival searches (P. G. Jonker et al. 2013; A. Glennie et al. 2015; F. E. Bauer et al. 2017; D. Alp & J. Larsson 2020; G. Novara et al. 2020; D. Lin et al. 2022; J. Quirola-Vázquez et al. 2023, 2025; M. Brightman et al. 2026). However, the vast majority lacked counterparts or redshift information, precluding definitive constraints on their origins or connection to SBO.

Thus far, the only bona fide X-ray SBO event was discovered serendipitously by the Neil Gehrels Swift Observatory's (Swift) X-ray Telescope (XRT; D. N. Burrows et al. 2005), which operates from 0.3–10 keV. During a scheduled XRT observation of galaxy NGC 2770, a bright X-ray flash (XRF 080109; XRFs belong to the broader class of FXTs) was detected in one of the spiral arms in the galaxy, lasting ~ 400 s (A. M. Soderberg et al. 2008). UV observations by Swift's Ultraviolet Optical Telescope (UVOT; P. W. A. Roming et al. 2005) 1.4 hr after the X-ray outburst revealed a brightening

UV and optical source, and later optical spectroscopic observations confirmed the associated optical transient was SN 2008D (R. A. Chevalier & C. Fransson 2008; P. A. Mazzali et al. 2008; A. M. Soderberg et al. 2008; D. Malesani et al. 2009; J. R. Maund et al. 2009; M. Modjaz et al. 2009). SN 2008D initially showed broad absorption features in its optical spectrum with no H or He lines (M. Modjaz et al. 2009), reminiscent of broad-lined Type Ic SNe (Type Ic-BL; A. V. Filippenko 1997; F. Taddia et al. 2019; G. P. Srinivasaragavan et al. 2024). However, SN 2008D evolved to show strong He absorption features, leading to the eventual classification of a Type Ib SN (A. M. Soderberg et al. 2008; J. R. Maund et al. 2009; M. Modjaz et al. 2009).

The discovery of XRF 080109/SN 2008D was groundbreaking, but its serendipitous nature and the absence of additional SBOs made it clear that a wide-field, sensitive UV/soft X-ray satellite was necessary to accrue a sample of SBOs. The Einstein Probe (EP; W. Yuan et al. 2022, 2025), or Tianguan mission, which began operations in 2024, is well-suited to regular detections and prompt alerts of new FXTs. EP's Wide-field X-ray Telescope (WXT), which has an instantaneous field of view of 3850 deg^2 , operates in the soft X-rays from 0.5 to 4 keV.

In just two years of operations, EP has detected $\gtrsim 100$ FXTs. Until recently, only five had been associated with SN Ic-BL counterparts (EP 240414a, 240801a, 250108a, 250304a, 250827b; H. Sun et al. 2025; R. A. J. Eyles-Ferris et al. 2025; H. Hamidani et al. 2025; W.-X. Li et al. 2025; J. C. Rastinejad et al. 2025; G. P. Srinivasaragavan et al. 2025a, 2025b; S. Srivastav et al. 2025; J. N. D. van Dalen et al. 2025; J.-H. Zheng et al. 2025; L. Cotter et al. 2026; A. P. C. van Hoof et al. 2026). The origins of the X-ray emission for these events remain ambiguous (e.g., R. A. J. Eyles-Ferris et al. 2025; G. P. Srinivasaragavan et al. 2025a; J.-H. Zheng et al. 2025). However, they are generally more luminous and spectrally harder compared to thermal SBO models, disfavoring a "classical" (nonthermal, nonrelativistic) SBO origin. Instead, these FXTs may be the product of relativistic jets, in line with observations of several FXTs associated with long gamma-ray bursts (GRBs; Y.-H. I. Yin et al. 2024; Y. Liu et al. 2025; R. Ricci et al. 2025).

In this Letter, we present our multiwavelength follow-up campaign and analysis of EP 260321a, the first EP FXT with properties consistent with expectations for SBO (Q. J. Huang et al. 2026a). In line with previously reported observations (e.g., M.-H. Lee et al. 2026; N. R. Tanvir et al. 2026), we show that EP 260321a originated in the galaxy SDSS J095942.88+002506.2 at $z = 0.0343$ (156 Mpc) and was accompanied by SN 2026gzf, rendering it the most nearby EP FXT with an associated SN discovered to date. In Section 2, we present our

new optical and radio observations of EP 260321a’s counterpart. In Section 3, we present analytic evidence that EP 260321a was the product of SBO, and infer properties of the circumstellar material (CSM) surrounding the progenitor star. In Section 4, we infer the properties of SN 2026gzf and contrast these with other stripped-envelope SNe (SESNe; Types Ib, Ic, Ic-BL), showing that SN 2026gzf is comparable to optically discovered Type Ic-BL SNe. In Section 5, we perform an analysis of EP 260321a’s host galaxy, SDSS J095942.88+002506.2. Finally, in Section 6, we review the combined picture of CSM surrounding the progenitor star from our multiwavelength probes and estimate the rate of EP-detected SBO signals. Throughout this work, we present all magnitudes in AB units and corrected for Galactic extinction of $E(B - V) = 0.02$ (unless otherwise specified; E. F. Schlafly & D. P. Finkbeiner 2011), and assume a Planck cosmology (Planck Collaboration et al. 2020).

2. Observations

2.1. X-Rays

EP’s WXT triggered on EP 260321a on UT 2026 March 21 12:23:07 (hereafter t_0 ; Q. J. Huang et al. 2026b). The event lasted for ~ 432 s. Observations were subsequently interrupted by EP’s Follow-up X-ray Telescope (FXT) automated follow-up observation of the field (Q. J. Huang et al. 2026a).³⁶ The average unabsorbed flux of the WXT observation in the 0.5–4 keV band was $8.0^{+2.2}_{-1.9} \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$. At the redshift $z = 0.0343$, the average flux corresponds to a peak luminosity of $\sim 2.2 \times 10^{44} \text{ erg s}^{-1}$. The WXT detection can be fit with a blackbody spectrum, with a peak energy $E_p = 0.164^{+0.04}_{-0.029} \text{ keV}$ (Q. J. Huang et al. 2026a).

FXT then observed EP 260321a at $\delta t = 12$ minutes (where δt is observed-frame time since t_0) and found an uncatalogued fading source within the WXT error circle at α (J2000) = $149^\circ 9287$ and δ (J2000) = $0^\circ 4177$ ($10''$ uncertainty radius; Q. J. Huang et al. 2026a). The average, unabsorbed flux in the 0.5–10 keV band was $(9.8 \pm 0.3) \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ (Q. J. Huang et al. 2026a). The FXT spectrum was well fit with a blackbody model with a peak energy $E_p = 0.121^{+0.03}_{-0.03} \text{ keV}$ (Q. J. Huang et al. 2026a). Q. J. Huang et al. (2026a) reported that its soft spectrum, rapid decay, and high luminosity rendered EP 260321a a promising SBO candidate.

In Figure 1, we contrast the X-ray light curve of EP 260321a against previous EP FXTs, Swift XRFs, and the X-ray light curves of LGRBs and Type Ic-BL SN 2020bvc (L. Izzo et al. 2020; A. Y. Q. Ho et al. 2020). With the exception of SBO XRF 080109, EP 260321a is the least luminous FXT, peaking nearly an order of magnitude below those of all previous FXT/XRF/GRB events. Overall, we observe a wide span in X-ray luminosity, nearly 10 orders of magnitude at < 1 day postexplosion, across a relatively small sample of events.

2.2. Photometry

Within the FXT localization, optical follow-up quickly discovered a blue, variable point source coincident with a star-forming galaxy at $z = 0.0343$ ($d_L = 156 \text{ Mpc}$; M.-H. Lee et al. 2026; N. R. Tanvir et al. 2026). The Zwicky Transient

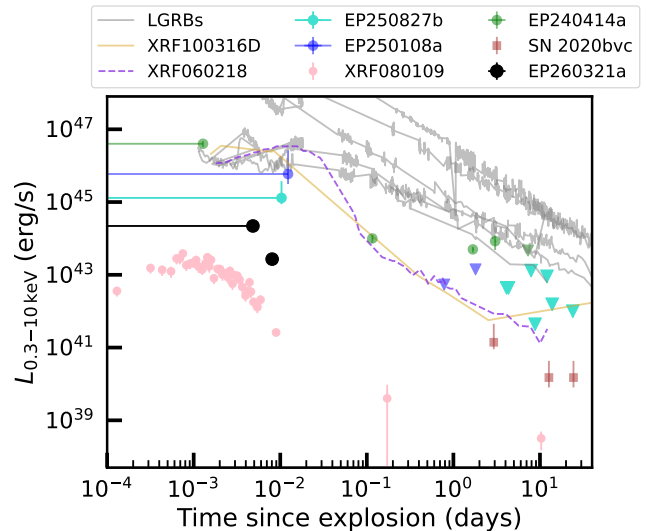


Figure 1. Comparison of the X-ray properties of EP 260321a from the GCNs (Q. J. Huang et al. 2026a) against the X-ray light curves of other SESNe (P. A. Evans et al. 2007, 2009; A. Y. Q. Ho et al. 2020; H. Sun et al. 2025; G. P. Srinivasaragavan et al. 2025a, 2025b). With the exception of SBO XRF 080109, EP 260321a is the least luminous FXT, peaking several orders of magnitude below FXTs associated with on-axis relativistic jets.

Facility (ZTF; E. C. Bellm et al. 2019; M. J. Graham et al. 2019; F. J. Masci et al. 2019; R. Dekany et al. 2020) detected the optical counterpart to EP 260321a, ZTF26aaonmha, in its regular surveying mode at $\delta t = 0.78$ day. In Section 2.3, we present evidence that this source is a SN counterpart to EP 260321a, SN 2026gzf, which resides in a blue “knot” within SDSS J095942.88+002506.2. The source was observed to be coincident with an existing compact, blue “knot” observed in Legacy Survey archival imaging (A. Dey et al. 2019), which we discuss further in Section 5.

We obtained optical photometry of SN 2026gzf in the *ugriz* bands with ZTF, the spectral energy distribution (SED) machine (SEDm; N. Blagorodnova et al. 2018; M. Rigault et al. 2019), and IO:O (R. M. Barnsley et al. 2016) mounted on the Liverpool Telescope (LT; Program ID: XJL24B16; PI: Bochenek) through the Fritz.science instance of SkyPortal (S. van der Walt et al. 2019; M. W. Coughlin et al. 2023) over $\delta t = 0.78$ –49.6 days. We further obtained *ugriz* photometry of SN 2026gzf observed by the Legacy Survey of Space and Time (LSST) conducted by the Vera Rubin Observatory (Rubin; Ž. Ivezić et al. 2019; T. Jegou du Laz et al. 2026; Vera C. Rubin Observatory Team 2026). Both ZTF and LSST observed variability ($\gtrsim 3$ – 5σ detections) at the location of SN 2026gzf several years to ~ 1 month prior to EP 260321a, potentially indicative of variability in the progenitor star. However, upon further examination, we are unable to confirm any of these pre-FXT detections as real (see Appendix A.1). We obtained additional *J*-band photometry of EP 260321a with WINTER (D. Frostig et al. 2022). We describe our photometric data reduction in Appendix Section A.1, show our light curves in Figure 2, and report our photometry in Appendix Table 4.

We fit a low-order polynomial to our *r*-band light curve of SN 2026gzf, finding a peak absolute magnitude of $M_r = -19.1$ at $\delta t = 14.2$ days. We compare the properties of SN 2026gzf to the wider sample of SESNe in Section 4.1. We determine the position of SN 2026gzf using acquisition imaging taken for the early GMOS spectra (Section 2.3). We stack the 60 s

³⁶ The Fermi Space Telescope was in the South Atlantic Anomaly at the time of the WXT trigger, and thus does not provide an upper limit on γ -ray emission from the source. Swift’s Burst Alert Telescope was not operating at the time of the trigger.

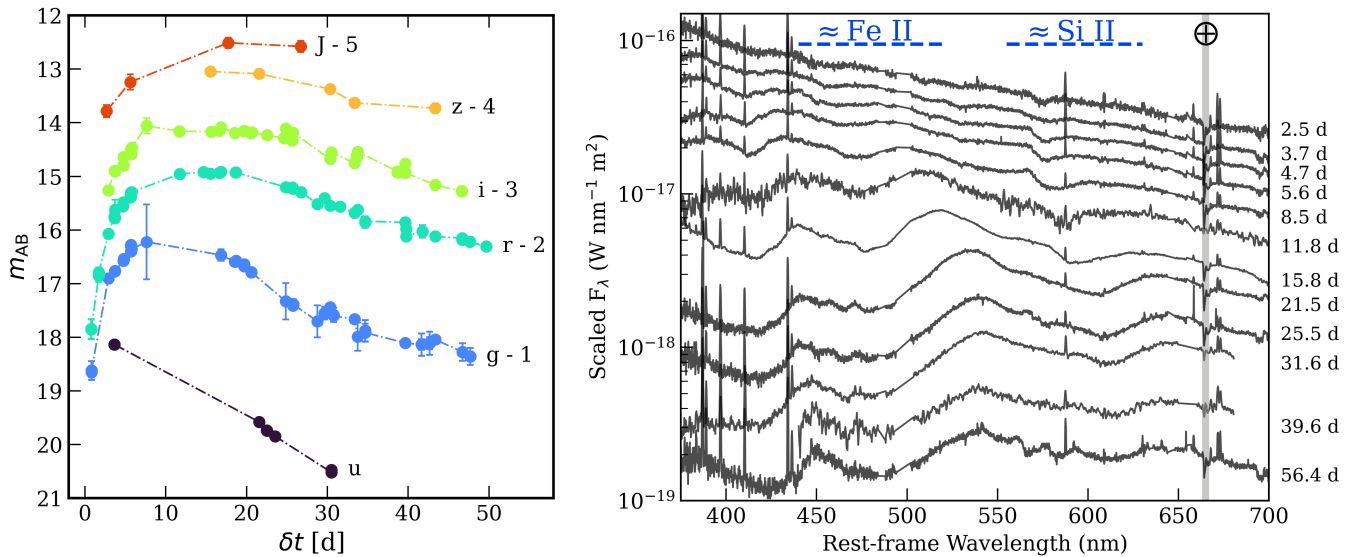


Figure 2. Optical observations of the Type Ic-BL counterpart to EP 260321a, SN 2026gzf. Left: our optical and near-IR light curve of SN 2026gzf. Right: sequence of GMOS, SOAR, and NGPS spectra of SN 2026gzf. We mask the regions of the emission lines of $H\alpha$, $H\beta$, and $[O\ III]$ for visibility. Spectra are not corrected for Galactic extinction, which is weak along the line of sight ($E(B - V) = 0.02$; E. F. Schlafly & D. P. Finkbeiner 2011).

acquisition images taken at $\delta t = 3.7, 4.7, 5.6, 8.5$ and 11.8 days with the pipeline Data Reduction for Astronomy from Gemini Observatory North and South (“DRAGONS,” K. Labrie et al. 2019), apply astrometry using astrometry.net (D. Lang et al. 2010), and determine SN 2026gzf’s position using Source Extractor (E. Bertin & S. Arnouts 1996). The final optical position is $\alpha = 09^h59^m42^s.8751$, $\delta = 00^{\circ}25'06''.454$, with a 3σ uncertainty radius of $0''.375$.

2.3. Spectroscopy

We obtained optical spectroscopy of SN 2026gzf over $\delta t = 2.5$ – 56.4 days with the Gemini Multi-Object Spectrographs (GMOS; I. M. Hook et al. 2004) mounted on the Gemini-North and South telescopes (Programs GN-2026A-Q-208, GS-2026A-Q-119, GS-2026A-Q-203; PIs: Rastinejad, Srinivasaragavan), the Next Generation Palomar Spectrograph (NGPS; H. Jiang et al. 2018) mounted on the Hale telescope (PI: Fremling), and the Goodman spectrograph (J. C. Clemens et al. 2004) mounted on SOAR (Program SOAR2026A-018; PI: Andreoni). We further obtained a near-IR spectrum of SN 2026gzf at $\delta t = 30$ days with the Folded-port InfraRed Echellette (FIRE; R. A. Simcoe et al. 2013) spectrograph on Magellan (PI: Anand). We describe our spectroscopic setup and data reduction in Appendix Section A.2 and present SEDm spectra, which are not used in our analysis as they provide similar temporal coverage and coarser spectral information, in Appendix Figure 17.

In Figure 2, we show our optical spectral series, smoothed using a Savitzky–Golay filter. In all spectra, we clearly detect strong emission lines from the underlying host galaxy, including $H\alpha$, $H\beta$, $H\delta$, $H\gamma$, $[O\ III]$, and $[S\ II]$, confirming the event distance at $z = 0.0343$. Our spectra do not show significant reddening nor Na I D absorption, indicating minimal dust along the line of sight from the host galaxy. We estimate the equivalent width (EW) of the Na I D line to be $EW \lesssim 0.167$ from the GMOS spectrum obtained on 2026 April 12, following (K. K. Das et al. 2023). Since Na I D absorption

is not consistently detected across all spectroscopic epochs, we treat the above estimate as an upper limit. Assuming the relation between host-galaxy extinction and Na I D EW, $A_v[\text{mag}] = 0.78(\pm 0.15) \times EW_{\text{Na I D}}[\text{\AA}]$ M. D. Stritzinger et al. (2018), we calculate a host extinction upper limit of $A_v < 0.13$ mag.

The spectra at early times ($\delta t \sim 3.7$ – 8.5 days) are remarkably blue and show weak, broad absorption features around ≈ 3800 – 4900 Å and ≈ 5200 – 6000 Å, which we ascribe to Fe II $\lambda 5169$ and Si II $\lambda 6355$. These broad absorption features become more prominent at $\delta t \gtrsim 12$ days. Across all epochs, our spectra do not show any obvious absorption at the expected locations of H or He lines, in contrast to SN 2008D (A. M. Soderberg et al. 2008; M. Modjaz et al. 2009). We classify our GMOS spectrum at $\delta t = 5.7$ days using SNID (S. Blondin & J. L. Tonry 2007) and find a best match to the Type Ic-BL SN 2006aj at 3 days postpeak. SN 2006aj was associated with the GRB/XRF 060218, whose peak X-ray luminosity was a factor of ~ 100 brighter than EP 260321a (Figure 1; S. Campana et al. 2006; M. Modjaz et al. 2006; A. M. Soderberg et al. 2006). We therefore conclude that SN 2026gzf is a Type Ic-BL SN.

All the spectra shown in Figure 2(b) are available in WISEREP.³⁷

2.4. Radio

We observed the field of SN 2026gzf with the Very Large Array (VLA) in its A configuration over five epochs. The first and fifth epochs were obtained on March 27 ($\delta t = 5.7$ days; 6, 10, 15, and 22 GHz) and May 15 ($\delta t = 54.5$ days; 6 and 10 GHz) under program 26A-385 (PI: Leung). We obtained three additional epochs at 6 GHz under program 25B-282 (PI: O’Dwyer) on April 4 ($\delta t = 12.8$ days), April 13 ($\delta t = 22.0$ days), and May 11 ($\delta t = 50.7$ days). For all data, we use J1007-0207 as a phase calibrator and 3C286 for flux density and bandpass calibration. We use J1024-0052 for pointing

³⁷ www.wiserep.org

Table 1

VLA Observations Covering the Position of EP 260321a/SN 2026gzf

t_{mid} (MJD)	δt (days)	ν (GHz)	F_ν (μJy)	Image rms (μJy)
61126.25	5.7	22.0	17	5.8
61126.27	5.7	14.9	8.0	7.2
61126.29	5.8	9.7	19	7.7
61126.31	5.8	6.2	19	5.8
61134.17	12.8	6.2	19	4.7
61143.06	22.5	6.2	20	4.9
61172.06	50.7	6.2	23	4.7
61175.05	54.5	9.8	21	8.5
61175.07	54.5	6.2	15	7.3

Note. As the measured 6 GHz flux (F_ν) is consistent across all epochs, we assume the radio emission is dominated by underlying star formation. We use F_ν as an upper limit in our modeling.

calibration in our higher-frequency 15 and 22 GHz observations under program 26A-385 because our phase calibrator was not bright enough for this purpose.

We use the NRAO pipeline-calibrated images (B. R. Kent et al. 2020) in CASA (CASA Team et al. 2022), comparing both standard calibrated continuum science-target data (`regcal`) and the corresponding products with self-calibration applied (`selfcal`) to calibrate and image the data. Flux densities were comparable within 1σ ; thus (`selfcal`) values are reported in Table 1. Images were cleaned down to the 5σ level and automated self-calibration on the science targets was carried out using automasking. After automated calibration and imaging, all data were also manually inspected for the presence of potential radio frequency interference and problematic antennae, with no outstanding issues found.

A faint radio counterpart to SN 2026gzf is detected at $>3\sigma$ in nearly all images at 6 GHz (Figure 3). For the radio epochs at ~ 13 –51 days, CASA `imfit` measurements each returned a point-like source component that may be as large as $0''.36 \times 2''$ with an integrated flux of $24.4 \pm 7.3 \mu\text{Jy}$. The position is slightly offset ($0''.197$) from our GMOS position (Figure 3). Given this offset and that the measured radio flux density at 6.2 GHz days remains unchanged within the errors across all epochs, we favor emission from star formation in the local environment as its source.

We employ measurements of this emission (F_ν in Table 1) as upper limits in our analysis and estimate the underlying star formation rate (SFR) from our radio observations in Section 5.3. We measure radio flux densities in the VLA images using the `imstat` tool in CASA. For each VLA epoch, we report the maximum flux density found within a circular region centered on $\alpha=09^{\text{h}}59^{\text{m}}42^{\text{s}}.872$, $\delta=00^{\circ}25'06''.38$, with a radius equal to the nominal VLA synthesized beam at the configuration and frequency setup of each observation ($0''.33$ for A-config C band). The rms of the noise is estimated from each image using a circular region of radius $\approx 10\times$ the nominal FWHM of the synthesized beam centered on the position of SN 2026gzf. We list all VLA observations in Table 1. We incorporate additional radio observations from the General Coordinate Network (GCNs) in our analysis (G. Gianfagna et al. 2026; A. J. Nayana et al. 2026).

In Figure 4, we plot our 6 GHz upper limits against the radio light curves of previous GRBs, FXTs, XRF 080109, and Type Ic-BL SN 2020bvc (S. R. Kulkarni et al. 1998; E. Waxman

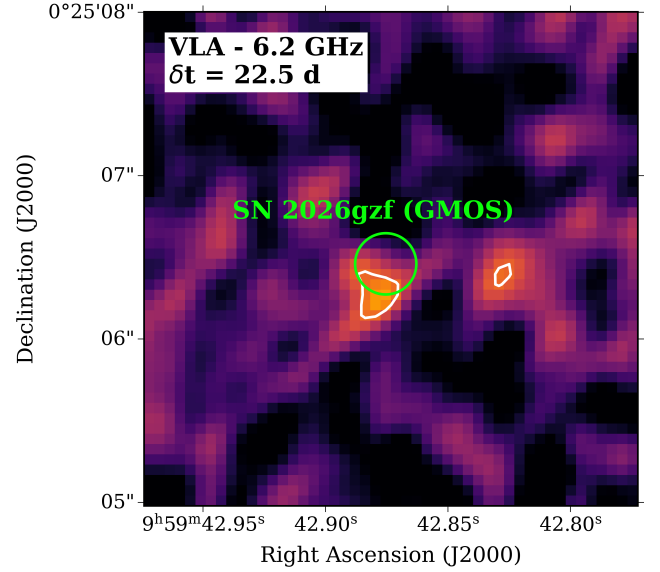


Figure 3. VLA 6.2 GHz image of the field of SN 2026gzf. White contours denote 3σ radio sources in the vicinity of SN 2026gzf, while the green ellipse shows SN 2026gzf's position measured from our GMOS imaging. The centers of the radio source and SN 2026gzf are offset by $0''.197$. The slight offset and absence of significant variation in the radio flux across epochs is consistent with underlying star formation rather than a radio counterpart to EP 260321a.

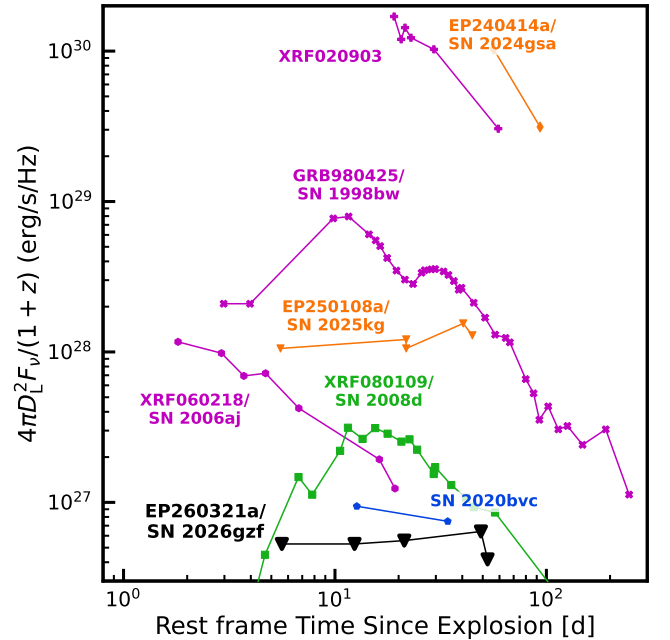


Figure 4. Comparison of radio upper limits of EP 260321a/SN 2026gzf with other GRBs, FXTs, and Type Ic-BL SNe (S. R. Kulkarni et al. 1998; E. Waxman et al. 1998; A. M. Soderberg et al. 2004, 2006, 2008; M. F. Bietenholz et al. 2009; A. Y. Q. Ho et al. 2020; J. S. Bright et al. 2025; G. P. Srinivasaragavan et al. 2025a). Our upper limits probe lower luminosities compared to all previous events shown.

et al. 1998; A. M. Soderberg et al. 2004, 2006, 2008; M. F. Bietenholz et al. 2009; A. Y. Q. Ho et al. 2020; J. S. Bright et al. 2025; G. P. Srinivasaragavan et al. 2025a). Our upper limits probe lower luminosities compared to all events shown. We further use these upper limits to constrain synchrotron emission from a relativistic on-axis jet and fast-moving SN ejecta in Section 3.

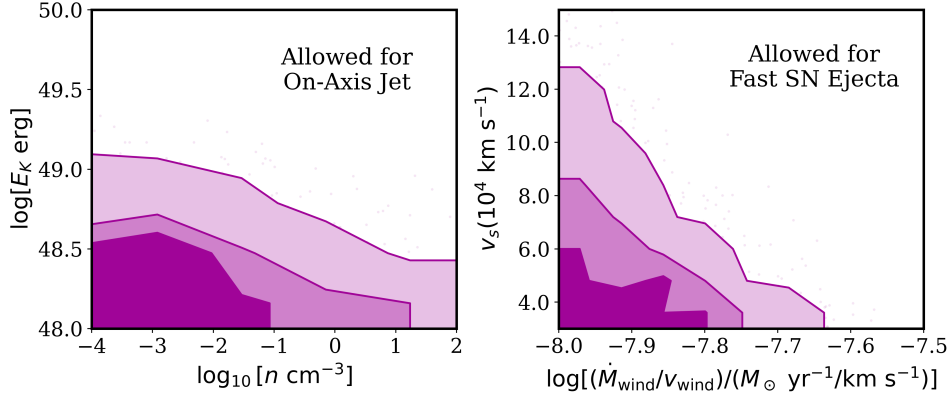


Figure 5. Constraints on models for synchrotron emission from an on-axis top-hat jet expanding into an ISM-like environment (left) and fast SN ejecta interacting with a wind-like CSM (right) from our radio upper limits. Contours show the 50%, 68%, and 90% probability regions. The radio limits constrain an on-axis jet to $E_{K, \text{iso}} \lesssim 10^{49}$ erg for typical massive-star environments ($n > 10^{-2} \text{ cm}^{-3}$) and imply low circumstellar mass loading, with fast-ejecta models favoring $\log_{10}[(\dot{M}/v_w)/(M_\odot \text{ yr}^{-1}/\text{km s}^{-1})] \simeq -7.8$

3. Analysis of X-Ray and Radio Components

3.1. Radio Constraints on On-axis Jet Energetics

The detection of GRBs coincident with some EP FXTs demonstrates that on-axis relativistic jets are a source of some FXTs (e.g., D. Frederiks et al. 2024; Y.-H. I. Yin et al. 2024; Y. Liu et al. 2025). We are thus motivated to investigate whether EP 260321a is the product of an on-axis jet. A signature of such jets is broadband synchrotron afterglow emission, observations of which can constrain the jet’s isotropic-equivalent energy ($E_{K, \text{iso}}$) and circumburst density (n ; e.g., J. Granot & R. Sari 2002). We use the afterglow modeling software *vegasafterglow* (Y. Wang et al. 2026) implemented in REDBACK to constrain the range of on-axis jet energies allowed by our deep radio upper limits (Section 2.4).

We model the radio data as 3σ upper limits using the REDBACK Gaussian upper limit likelihood. We assume an on-axis top-hat jet expanding into a constant-density interstellar medium (ISM). We fix the viewing angle to $\theta_{\text{obs}} = 0$, set the wind-like density parameter to a negligible value, and fix the microphysical parameters to $\epsilon_e = \epsilon_B = 0.1$. We adopt broad priors on the isotropic-equivalent kinetic energy and density, $\log_{10}(E_{K, \text{iso}}/\text{erg}) = 48\text{--}54$ and $\log_{10}(n/\text{cm}^{-3}) = -5$ to -2 , and allow the jet opening angle, initial Lorentz factor, and electron energy distribution index to vary over $\theta_c = 0.05\text{--}0.25$ rad, $\Gamma_0 = 10\text{--}1000$, and $p = 2.5\text{--}3.0$. We emphasize that as the radio data are all nondetections, the posterior should be interpreted as the region of parameter space that remains allowed by the limits under these assumptions, rather than as any strong constraint on the properties of a potential afterglow.

The radio upper limits strongly disfavor a normal energetic on-axis GRB-like afterglow. The allowed on-axis top-hat posterior has $\log_{10}(E_{K, \text{iso}}/\text{erg}) = 48.4$ with a 90% credible interval of 48.0–49.1, corresponding to a 95th-percentile upper bound of $E_{K, \text{iso}} \simeq 1.2 \times 10^{49}$ erg. We show the $\log_{10}(E_{K, \text{iso}}/\text{erg}) - \log_{10}(n/\text{cm}^{-3})$ parameter space allowed by our limits in Figure 5 and the full corner plot in Appendix Figure 13. Restricting to densities $n > 10^{-2} \text{ cm}^{-3}$, the 95th-percentile upper bound is $E_{K, \text{iso}} \simeq 7.8 \times 10^{48}$ erg. Higher energies are only possible for very low-density environments, and densities $n \lesssim 10^{-2} \text{ cm}^{-3}$ are uncommon for long GRBs (A. Panaitescu & P. Kumar 2002; T. Kangas & A. S. Fruchter 2021; G. Schroeder et al. 2025), which are likely to trace

broadly similar massive-star environments to Type Ic-BL SN 2026gzzf. These limits therefore disfavor an ordinary on-axis GRB jet as the origin of EP 260321a.

Our radio observations span a limited time window $\delta t = 5.7\text{--}54.5$ days after explosion and are therefore less constraining for off-axis jets, structured jets, or jets in extremely low-density environments. We find that an off-axis top-hat jet with standard microphysics with $\theta_{\text{obs}}/\theta_c \simeq 7.7$ and a broad allowed $E_{K, \text{iso}}$ range extending to normal GRB-like energies is allowed by our upper limits. A Gaussian-structured jet gives a similar conclusion, with $\theta_{\text{obs}}/\theta_c \simeq 7.0$ and broad allowed energies. An on-axis jet can also be hidden if the microphysical parameters are allowed to be small, with representative posterior values $\log_{10} \epsilon_e \simeq -2.0$ and $\log_{10} \epsilon_B \simeq -4.0$. By contrast, an on-axis GRB or low-luminosity GRB ($E_{K, \text{iso}} \gtrsim 10^{49}$ erg; Z. Cano et al. 2017a) with standard microphysics survives only in an extremely low-density environment, $\log_{10}(n/\text{cm}^{-3}) \simeq -7.7$, which we regard as physically implausible given SN 2026gzzf’s environment (Section 5). We further find that allowing ϵ_B to vary freely over $-4.0 \leq \log_{10} \epsilon_B \leq -1.0$ only weakens the 95th-percentile upper limit to $E_{K, \text{iso}} \leq 5 \times 10^{49}$ erg for $n \lesssim 10^{-2} \text{ cm}^{-3}$ (Appendix Figure 14), still below a typical on-axis GRB afterglow (Z. Cano et al. 2017a). Thus, the radio data rule out an ordinary on-axis GRB-like afterglow under standard assumptions (Figure 5), but they do not exclude an off-axis jet, a structured weak jet, or a jet with unusually low microphysical efficiencies. Late-time radio observations will probe an off-axis jet, which may be distinguished by its light-curve shape.

3.2. Analytic Evidence for X-Ray SBO

We next investigate whether SBO, which was strongly favored to explain the FXT preceding SN 2008D (P. A. Mazzali et al. 2008; A. M. Soderberg et al. 2008; M. Modjaz et al. 2009), is a plausible explanation for EP 260321a. We use the treatment presented in A. Haynie & A. L. Piro (2021) to probe whether emission due to subrelativistic SBO of ejecta in a CSM environment can adequately describe the WXT detection (see Section 2.1), assuming that diffusion is the dominant rate-

limiting process. The SBO's rise time can be represented as

$$t_r = \frac{R_e^2}{R_d v_t}, \quad (4)$$

where R_e is the radius of the CSM and v_t is the characteristic velocity of the shock. t_r is defined by how quickly photons can diffuse out of the extended envelope from the depth of the SBO, R_d . R_d is defined as

$$R_d = \frac{\kappa_C D v_t}{c}, \quad (5)$$

where κ_C is the opacity of the CSM, and D is the mass-loading factor,

$$D = \frac{\dot{M}}{4\pi v_t}. \quad (6)$$

Since M_e , the mass of CSM, $\sim 4\pi R_e D$, we integrate the expression for D with respect to mass and substitute into the expression for R_d to get

$$R_d = \frac{\kappa_C v_t}{c} \frac{M_e}{4\pi R_e}. \quad (7)$$

After substituting this expression into t_r , we find

$$t_r = \frac{4\pi R_e^3 c}{\kappa_C M_e v_t^2}. \quad (8)$$

Since we are in the diffusion-dominated regime, the luminosity of the SBO is

$$L_{\text{SBO}} = \frac{E_{\text{SBO}}}{t_r} = \frac{4\pi c R_e v_t}{\kappa} \approx 4\pi c v_t^3, \quad (9)$$

where E_{SBO} is the SBO's energy (see A. Haynie & A. L. Piro (2021) for a full derivation).

If the X-ray prompt emission is generated through the SBO, the SBO's rise time should be similar to the rest-frame timescale of the prompt emission. We only have a lower limit on this timescale of ~ 430 s (Section 2.1), though we note that EP FXT SNe EP 250108a and EP 250827b both had prompt emission timescales on the order of ~ 1000 s (W.-X. Li et al. 2025; G. P. Srinivasaragavan et al. 2025b). We crudely perform this calculation assuming $t_r \sim 430$ – 1000 s given the uncertainty in timescale. We solve Equations (5) and (6) in parallel, using a characteristic value of $\kappa = 0.2 \text{ cm}^2 \text{ g}^{-1}$ (G. P. Srinivasaragavan et al. 2025b). We do not have good constraints on the initial shock velocity, as the earliest spectrum we obtain a velocity measurement for is at ~ 2.5 days (see Section 4.2), where $v_t \sim 0.1c$. The maximum velocity allowed for a subrelativistic SBO is $\sim 0.35c$, consistent with the maximum value of the ejecta derived from the modeling of the radio upper limits along with the photospheric velocity at early times (Section 3.3), and just below the relativistic threshold where pair production begins to affect the emission. Thus we can comfortably assume $v_t \sim 0.15$ – $0.35c$. Solving Equations (5) and (6) in tandem using the above assumptions, we derive $R_e \sim 2.1 \times 10^{12}$ – 5.0×10^{12} cm and $M_e \sim 2 \times 10^{-7}$ – $6.0 \times 10^{-6} M_\odot$. The radius derived is consistent with the radii expected from slightly inflated Wolf-Rayet progenitors (J. H. Shiode & E. Quataert 2014) and that found for XRF 080109/SN 2008D ($R_e \sim 4 \times 10^{12}$ cm; A. M. Soderberg et al. 2008; G. Svirski & E. Nakar 2014).

Next, we compute the expected peak energy from the SBO to test consistency with the reported peak energy of the WXT observation of ~ 0.16 keV (Section 2.1). If the radiation was fully thermalized, we expect a blackbody spectrum and a temperature that goes as

$$T_{\text{BB}} \approx \left(\frac{L_{\text{SBO}}}{4\pi R_e^2 \sigma_{\text{SB}}} \right)^{1/4}, \quad (10)$$

where σ_{SB} is the Stefan–Boltzmann constant. Substituting our known values into this expression, we find $T_{\text{BB}} \sim 3.3$ – 5.0×10^5 K, or a peak energy of 0.03–0.05 keV. However, we need to ensure that the radiation is in true thermal equilibrium, and compute the thermal coupling coefficient in an expanding gas from E. Nakar & R. Sari (2010) to check this, given as

$$\eta \approx \frac{7 \cdot 10^5 \text{ s}}{\min\{t, t_d\}} \left(\frac{\rho}{10^{-10} \text{ g/cm}^3} \right)^{-2} \left(\frac{kT_{\text{BB}}}{100 \text{ eV}} \right)^{7/2}, \quad (11)$$

where k is the Boltzmann constant, and $\min\{t, t_d\}$ is the minimum time between the characteristic timescale and the diffusion time. The characteristic timescale here is the end of the prompt emission timescale of $t \sim 430$ – 1000 s. If $\eta < 1$, then the approximation of thermal equilibrium holds, and the observed temperature $T = T_{\text{BB}}$. However, if $\eta > 1$, then emission will be dominated by free–free processes, and the spectrum resembles a Wien spectrum that is also affected by Comptonization of photons by neighboring electrons (E. Nakar & R. Sari 2010). We compute η , substituting our known values and taking into account that the density increases by a factor of 7 due to compression of the shock (E. Waxman & B. Katz 2017). Through this calculation, we derive $\eta \sim 4$ – 141 for the range of densities derived earlier. Therefore, the approximation of thermal equilibrium does not hold. Indeed, free–free emission will dominate, and the spectrum can be represented by a Wien spectrum characterized by a temperature

$$T\xi(T)^2 = T_{\text{eq}}\eta^2, \quad (12)$$

where $\xi(T)$ is the Comptonization correction factor, given by

$$\xi(T) \approx \max \left\{ 1, \frac{1}{2} \ln[y_{\text{max}}](1.6 + \ln[y_{\text{max}}]) \right\}, \quad (13)$$

where y_{max} is the Compton parameter,

$$y_{\text{max}} \equiv \frac{kT}{h\nu_{\text{min}}} = 3 \left(\frac{\rho}{10^{-9} \text{ g/cm}^3} \right)^{-1/2} \left(\frac{T}{100 \text{ eV}} \right)^{9/4}. \quad (14)$$

We solve Equation (9) for T , substituting our known values, and find $T \sim 0.15$ – 3.2 keV, consistent with the value found from the WXT detection. We therefore conclude that analytic arguments support an SBO origin for EP 260321a.

3.3. REDBACK Evidence for SBO and Constraints on CSM

Having established that EP 260321a is analytically consistent with SBO, we next use REDBACK to test whether the X-ray and radio data are consistent with a compact SBO origin. The public X-ray data provide only sparse temporal information. We therefore treat the X-ray modeling as a

consistency check rather than as a unique inference of the CSM structure. We further use the radio data to constrain the circumstellar environment at larger radii.

For the X-rays, we fit the WXT and FXT luminosities with an SBO-like model (C. L. Fryer et al. 2026) that computes the fading X-ray luminosity from shocked material emerging from an effective emitting area. The free parameters are the injected energy, E_{in} , the slope of the high-velocity ejecta tail, the maximum Lorentz factor, Γ_{max} , the emitting area, A , the local density, ρ , the radiative efficiency, f_{eff} , and an emergence time, t_{emerge} . In particular, the effective emitting area, A , parameterizes the total surface area of the shocked material contributing to the X-ray emission. It is related to an effective radius by $R_{\text{eff}} = (A/\pi)^{1/2}$, which can represent either a full spherical breakout surface ($A = 4\pi R^2$) or a smaller, patchy or aspherical region if the breakout is geometrically confined. This could be the case for a clumpy CSM or a preferential viewing direction through a low-opacity channel. Values of $R_{\text{eff}} \ll R_{\text{progenitor}}$ would therefore suggest an aspherical or partial breakout. Γ_{max} is the maximum Lorentz factor of the ejecta, setting the high-energy cutoff of the velocity distribution and the characteristic velocity of the fastest-moving material. For a subrelativistic shock, $\Gamma_{\text{max}} \lesssim$ a few, while $\Gamma_{\text{max}} \sim 10 - 100$ is appropriate for relativistic or mildly relativistic breakouts. The parameter p describes the power-law index of the Lorentz factor distribution of the fastest-moving shocked ejecta, $dN/d\Gamma \propto \Gamma^{-p}$. Steeper values of p concentrate the energy in slower (lower- Γ) material, while shallower values allow a significant high-velocity tail. This determines how rapidly the X-ray luminosity declines after the shock emerges, since higher- Γ ejecta radiate more energetically but exhaust their energy faster.

We note that Γ_{max} characterizes the velocity of the fastest-moving, outermost ejecta responsible for the X-ray SBO emission. This fast component constitutes a negligibly small mass fraction compared to the bulk ejecta, whose characteristic expansion velocity, v_{ej} , is independently constrained by the optical SN models (Section 4.4). This parameterization is not identical to the analytic variables in Section 3.2; in particular, the emitting area can represent a patchy or aspherical breakout surface rather than the full spherical radius as was previously assumed.

The SBO model (Appendix Figure 12) reproduces the rapid decline from WXT to FXT and prefers $\log_{10}(E_{\text{in}}/\text{erg}) = 47.47$ with a 90% credible interval of 46.68–50.03, $\Gamma_{\text{max}} \simeq 19$ with a broad 90% interval of 2.3–80, and $t_{\text{emerge}} \simeq 200$ s. The inferred effective emitting radius, $R_{\text{eff}} = (A/\pi)^{1/2}$, is 1.5×10^{10} cm, with a broad 90% interval of 1.0×10^9 – 6.4×10^{11} cm. This radius is somewhat smaller than that from XRF 080109 (A. M. Soderberg et al. 2008; G. Svirski & E. Nakar 2014). However, given the limited and preliminary public X-ray data, we do not conclude they are inconsistent at present. The posterior on density is also broad, with a median $\rho \simeq 4.5 \times 10^{-8} \text{ g cm}^{-3}$. Given this limited X-ray information, these should not be taken as strong constraints but rather as further support (when combined with the analytical calculation) toward establishing the SBO origin of EP 260321a. In particular, this supports that a compact, rapidly cooling SBO component can account for the X-ray luminosity evolution without requiring a luminous, long-lived relativistic afterglow.

The radio data probe a different physical scale: synchrotron emission from the fastest SN ejecta interacting with the outer wind-like CSM. We model this component in REDBACK using

the synchrotron massloss model (R. A. Chevalier & C. Fransson 2017). For simplicity, we assume $\epsilon_e = \epsilon_B = 0.1$, a range on $p = 2.5$ – 3.0 , allow shock velocities $v_s = 3 \times 10^4$ – $1.5 \times 10^5 \text{ km s}^{-1}$ ($\simeq 0.1$ – $0.5c$), and fit the wind mass-loading parameter $\dot{M}/v_w$ for which $\dot{M}$ is the mass-loss rate and v_w is the velocity of the wind. The posterior is again an allowed-region constraint because the radio data are upper limits (Figure 5). We find $v_s = 5.3 \times 10^4 \text{ km s}^{-1}$ with a 90% interval of 3.1×10^4 – $1.1 \times 10^5 \text{ km s}^{-1}$ ($\beta \simeq 0.18$, with a 90% interval of 0.10–0.36), and

$$\log_{10} \left[\frac{\dot{M}/v_w}{M_{\odot} \text{ yr}^{-1}/(\text{km s}^{-1})} \right] \leq -7.92. \quad (12)$$

We show the allowed light curves from our space compared to the full span of light curves allowed by our prior ranges in Appendix Figure 15, highlighting that the posterior distributions are data-driven. In addition to the radius derived from the X-ray SBO signal, that EP 260321a’s SN counterpart is of Type Ic-BL further favors a Wolf–Rayet progenitor (e.g., S. E. Woosley & A. Heger 2006). For a Wolf–Rayet-like wind velocity of $v_w = 1000 \text{ km s}^{-1}$ (C. Cappa et al. 2004), the median mass-loss rate corresponds to $\dot{M} \lesssim 1.2 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$. This is consistent with the $\dot{M} \approx 10^{-5} M_{\odot} \text{ yr}^{-1}$ inferred from radio detections of SN 2008D (A. M. Soderberg et al. 2008; A. J. van der Horst et al. 2011), and observed mass-loss rates in Wolf–Rayet stars (C. Cappa et al. 2004). The fastest allowed ejecta require lower mass loading; conditioning on $v_s > 0.15c$ gives a 95th-percentile upper limit of $\log_{10}[(\dot{M}/v_w)/(M_{\odot} \text{ yr}^{-1}/\text{km s}^{-1})] \lesssim -7.77$.

Taken together, the X-ray and radio constraints favor a picture in which the X-rays arise from a compact SBO component close to the progenitor, while the radio limits require that any faster ejecta encounter only modest mass loading at larger radii. This is consistent with SBO from a compact Wolf–Rayet progenitor or a small amount of nearby material, and disfavors an ordinary on-axis GRB afterglow (e.g., A. Panaitescu & P. Kumar 2002; T. Kangas & A. S. Fruchter 2021). It does not exclude aspherical structure, clumpy CSM (e.g., C. L. Fryer et al. 2020), or an off-axis jet, which require later-time radio observations to test robustly. Overall, we find that the inferred properties of EP 260321a’s progenitor are broadly consistent with those of XRF 080109/SN 2008D.

4. Analysis of SN 2026gzf

4.1. Comparison to SESNe Light Curves

Having established that EP 260321a was likely the product of SBO, we next investigate the properties of its Type Ic-BL counterpart, SN 2026gzf, and contextualize these with SESNe. First, we compare SN 2026gzf’s light curve to the range of SESNe discovered with and without high-energy counterparts (FXTs, GRBs). In Figure 6, we plot SN 2026gzf’s rest-frame r -band light curve against optically discovered SNe Ic-BL (G. P. Srinivasaragavan et al. 2024), optically discovered Type Ib/c SNe (M. R. Drout et al. 2011), GRB SNe (T. Matheson et al. 2003; Z. Cano et al. 2011; A. Clocchiatti et al. 2011; E. F. Olivares et al. 2012; A. J. Levan et al. 2014; D. A. Perley et al. 2014; J. Greiner et al. 2015; Z. Cano et al. 2017b; L. Izzo et al. 2019; Y. D. Hu et al. 2021; J. C. Rastinejad et al. 2024) and previous FXT SNe (including SBO SN 2008D; N. Mirabal et al. 2006; M. Modjaz et al. 2006; A. M. Soderberg et al. 2006; A. M. Soderberg et al. 2008; M. Modjaz et al. 2009;

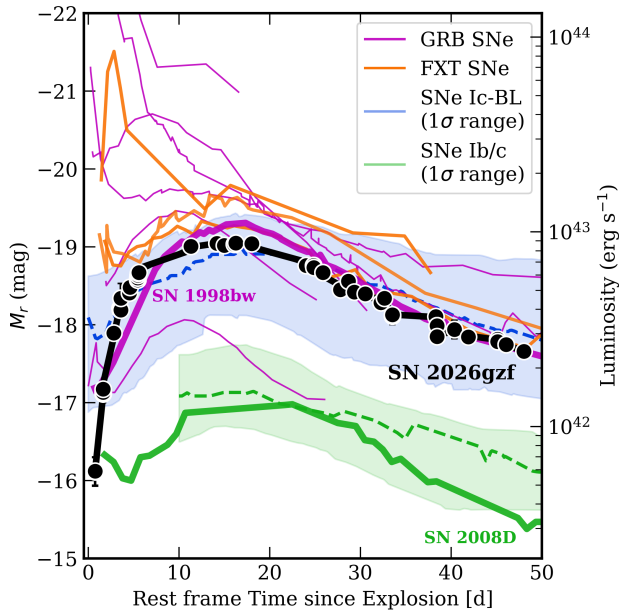


Figure 6. Comparison of rest-frame r -band light curves for SN 2026gzf (black) against GRB (magenta; including synchrotron afterglow emission) and FXT (orange), optically discovered Type Ic-BL (blue; G. P. Srinivasaragavan et al. 2024), and Ib/c (green; M. R. Drout et al. 2011) SNe. We plot the median (dashed line) and 1σ range (shaded regions) of Types Ib/c and Ic-BL SNe. We highlight GRB SN 1998bw and Type Ib SBO SN 2008D with thick solid lines.

J. C. Rastinejad et al. 2025; G. P. Srinivasaragavan et al. 2025a; S. Srivastav et al. 2025). For the GRB and FXT SNe, we set $\delta t = 0$ to be the time of the GRB or FXT trigger and do not remove emission from the synchrotron afterglow or early shock cooling. For the optically discovered Type Ic-BL and Ib/c SNe, we normalize the light-curve peak times to the rest-frame peak time of SN 2026gzf. We then linearly interpolate the r -band light curves and determine the 1σ confidence interval on the range of Type Ic-BL and Ib/c light curves. We correct all light curves for Galactic extinction in the direction of the burst (E. F. Schlafly & D. P. Finkbeiner 2011). We further correct SN 2008D and SN 2010bh for notable host extinction along the line of sight (A. M. Soderberg et al. 2008; R. L. C. Starling et al. 2011).

SN 2026gzf is well within the 1σ range of Type Ic-BL SN r -band light curves and consistent with the range of light curves of GRB and FXT SNe (Figure 6). Its peak magnitude of $M_r \sim -19.1$ mag is more luminous than 75% of optically discovered Type Ic-BL SNe (F. Taddia et al. 2019; G. P. Srinivasaragavan et al. 2024). Compared to the median Type Ic-BL light curve, SN 2026gzf exhibits a more rapid rise at $\delta t \lesssim 1$ week. However, not all Type Ic-BL are well-sampled at these early epochs (G. P. Srinivasaragavan et al. 2024). Further, GRB and FXT SNe are often contaminated by afterglow emission on these timescales. Finally, we highlight that SN 2026gzf is ≈ 10 times more luminous compared to the Type Ib SBO SN 2008D, though this is in keeping with the medians of their respective SN types (Figure 6).

4.2. Expansion Velocities

We next measure the velocity of the $\lambda 5169$ Å Fe II line for our spectra of SN 2026gzf taken with GMOS, NGPS, and SOAR. The relative blueshift of the middle of the broad Fe II

absorption trough is a well-tested proxy for the photospheric expansion velocity (v_{ph}) of the SN (M. Modjaz et al. 2016). We use the open-source SESNSpectraLib³⁸ (Y.-Q. Liu et al. 2016; M. Modjaz et al. 2016) package to smooth each spectrum and use SESNSpectraPCA³⁹ to calculate the blueshift of the Fe II line relative to standardized Type Ic spectroscopic templates at similar phases. We calculate the total uncertainty by adding the uncertainty on the velocity of the mean Type Ic template in quadrature with the uncertainty on the relative blueshift.

We show our expansion velocity measurements of SN 2026gzf in Figure 7 against other FXT, GRB, Type Ic-BL and Ic SNe (K. Iwamoto et al. 1998; P. A. Mazzali et al. 2000, 2002, 2003, 2006; E. Pian et al. 2006; D. N. Sauer et al. 2006; P. A. Mazzali et al. 2008; M. Modjaz et al. 2009; F. Taddia et al. 2019; A. Corsi et al. 2023; S. Anand et al. 2024; G. P. Srinivasaragavan et al. 2024, 2025b). Overall, SN 2026gzf falls well within the range of expansion velocities for SESNe. At our earliest epoch ($\delta t = 2.5$ days), SN 2026gzf expanded at a greater velocity ($v_{ph} = 37, 700^{+10600}_{-5200}$ km s⁻¹) compared to FXT SN 2008D and the handful of Type Ic-BL SNe observed at a similar epoch. However, we note that this temporal region is poorly sampled for most event classes, in particular for GRB SNe due to afterglow contamination.

4.3. Near-IR Search for He Absorption

The amount of He present in the ejecta of Type Ic-BL SNe, and thus the extent to which He stripping occurs prior to core collapse, is currently poorly constrained by observations. When correcting for blueshifting using our Fe II velocities (Section 4.2), we do not observe significant absorption at the expected positions of He I (e.g., $\lambda\lambda\lambda 4471, 5876, 6678, 7061$) in our optical spectra.

We search for He absorption in our Magellan/FIRE near-IR spectrum of SN 2026gzf, taken at $\delta t = 30$ days. He produces stronger absorption features in the near-IR ($\lambda 1.083$ μ m and $\lambda 2.058$ μ m) compared to the optical lines. However, due to the nearby C I $\lambda 1.0693$ μ m and Mg II $\lambda 1.0927$ μ m lines, the detection of absorption at ~ 1 μ m is difficult to ascribe to He I without full radiative transfer calculations. He I $\lambda 2.058$ μ m is comparatively less contaminated, but often poorly constrained due to low signal-to-noise or overlap with Telluric lines.

In Figure 8 we compare the near-IR spectrum of SN 2026gzf to that of Type Ic-BL SNe SN 2025 kg (associated with EP 250108a; J. C. Rastinejad et al. 2025), SN 1998bw (associated with GRB 980425; F. Patat et al. 2001) and SN 2022crr (no known high-energy counterpart; S. Tinyanont et al. 2024). We observe an absorption feature at ~ 1 μ m for SN 2026gzf, in keeping with the near-IR spectra of previous SESNe (F. Patat et al. 2001; S. Tinyanont et al. 2024; J. C. Rastinejad et al. 2025; B. Schneider et al. 2026). However, we do not observe significant absorption at the expected location of the He I $\lambda 2.058$ μ m feature. Due to low signal-to-noise in the region, we cannot rule out that this absorption may be present. Robust constraints on the presence of He I absorption necessitate full radiative transfer calculations (e.g., M. Shahbandeh et al. 2022; J. Lu et al. 2026), outside the scope of this work.

³⁸ <https://github.com/metal-sn/SESNSpectraLib>

³⁹ <https://github.com/metal-sn/SESNSpectraPCA>

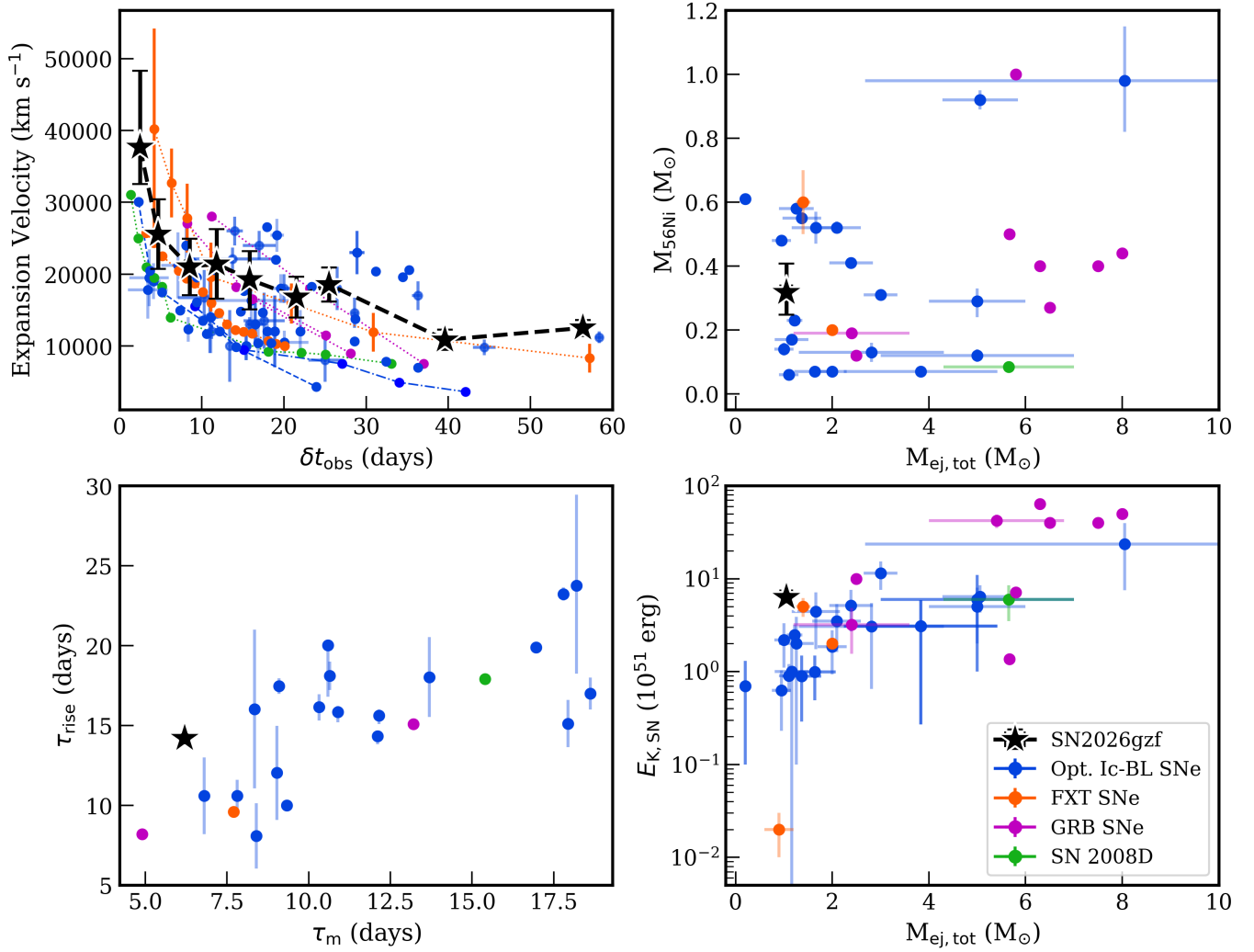


Figure 7. Comparison of the properties of SN 2026gzf derived from our analysis (black stars; Section 4) with GRB (magenta), FXT (orange; including Type Ib SN 2008D, which is shown in green), and optically discovered Type Ic-BL SNe (blue). In the top left panel we plot the SN expansion velocities (Section 4.2; K. Iwamoto et al. 1998; P. A. Mazzali et al. 2000, 2002, 2003, 2006; E. Pian et al. 2006; D. N. Sauer et al. 2006; P. A. Mazzali et al. 2008; M. Modjaz et al. 2009; F. Taddia et al. 2019; A. Corsi et al. 2023; S. Anand et al. 2024; G. P. Srinivasaragavan et al. 2024, 2025b). In the right top and bottom panels, we compare SN 2026gzf’s M_{ej} , M_{Ni} , and E_K inferred from our CSM + ^{56}Ni model (Section 4.4.5). In the bottom left panel, we plot the time from explosion to peak (τ_{rise}) against the diffusion timescale (τ_m), highlighting that SN 2026gzf’s diffusion timescale is relatively fast compared to other events (J. D. Lyman et al. 2016; G. P. Srinivasaragavan et al. 2024). Overall, SN 2026gzf’s properties are most consistent with optically discovered Type Ic-BL SNe.

4.4. REDBACK SN Modeling

We model the Galactic extinction-corrected, well-sampled optical and near-IR light curve of SN 2026gzf with REDBACK (N. Sarin et al. 2024) to infer its explosion parameters and to test the presence of a heating channel beyond some centrally concentrated radioactive material. We explore five models to fit the light curve of SN 2026gzf: a one-zone Arnett-like ^{56}Ni model, a ^{56}Ni mixing model, a magnetar model, a pure CSM interaction model, and a combined CSM interaction and ^{56}Ni model. For all fits, we use the nested sampler *Pymultinest* (J. Buchner et al. 2014) through *Bilby* (G. Ashton et al. 2019). The likelihood includes both detections and upper limits, with the latter treated using the REDBACK Gaussian upper limit likelihood. Unless otherwise specified, we use broad, uninformative uniform or log-uniform priors for all parameters.

All models are fit in observed-frame magnitude space, and assume an initially expanding photosphere that begins to recede once the ejecta temperature drops to T_{floor} . The SED is assumed to be a blackbody. This is a useful approximation for fitting the broadband light curve, but it does not model line blanketing, spectral features, or deviations from a single thermal photosphere. These general limitations are applicable to all models we consider.

Throughout, we fix the redshift to $z = 0.0343$ and include host-galaxy extinction, A_V , as a nuisance parameter using a Fitzpatrick extinction law with $R_V = 3.1$ (E. L. Fitzpatrick 1999). For the CSM models, we also run physically constrained fits using the standard REDBACK CSM constraints; the CSM photosphere must sit between the inner and outer CSM radii, and the CSM diffusion time must be shorter than the shock-crossing time. These constraints are critical to preventing CSM configurations that are mathematically

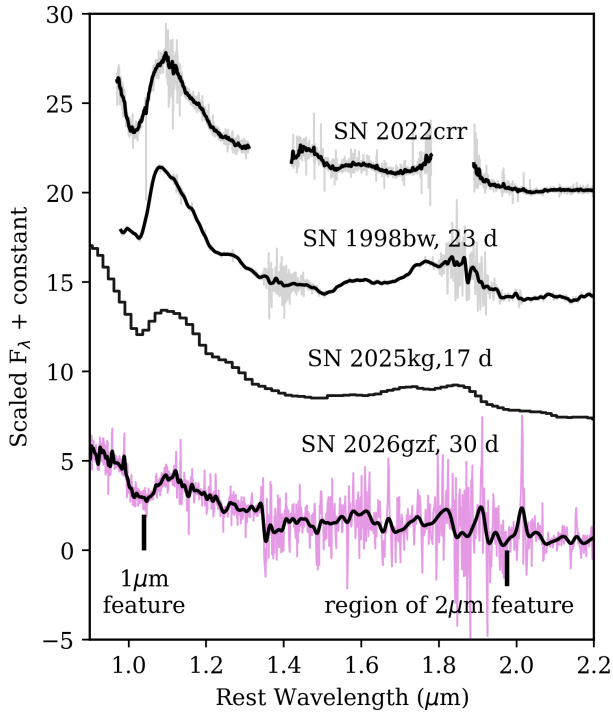


Figure 8. Magellan/FIRE near-IR spectrum of SN 2026gzf (bottom), compared to near-IR spectra of past Type Ic-BL SNe (F. Patat et al. 2001; S. Tanyanont et al. 2024; J. C. Rastinejad et al. 2025). We mask regions contaminated by telluric features. While we observe an absorption feature $\sim 1 \mu\text{m}$, the expected $2 \mu\text{m}$ feature is not well detected in our FIRE spectrum due to low signal-to-noise, precluding a firm detection of He I.

allowed by the luminosity prescription but physically self-inconsistent. We fix the optical opacity to $\kappa = 0.07 \text{ cm}^2 \text{ g}^{-1}$ for all models apart from the ^{56}Ni mixing fit, where the model includes an internal temperature-dependent opacity parameterization. This value is typical of Type Ic-BL SN modeling (e.g., G. P. Srinivasaragavan et al. 2024).

The model light-curve credible regions are shown in Figure 9. Overall, we find that the combined CSM+ ^{56}Ni model gives the strongest physical and statistical support among the models explored. As we will discuss in Section 6, the model also provides a natural self-consistent picture for the multiwavelength properties and the progenitor of this event. We emphasize that the following modeling does not fold in any information from our radio or X-ray analysis above, as well as any spectra. Instead, it is simply exploring how well we can fit the SN light curve from a data and physical perspective. We compare our constraints on CSM properties to those from the EP X-ray emission and radio nondetections in Section 6.1.

4.4.1. One-zone Arnett Model

We first model the light curve using a one-zone Arnett-like model (W. D. Arnett 1982; S. Valenti et al. 2008). This model assumes that the radioactive heating from ^{56}Ni and ^{56}Co decay is a single zone and the raw radioactive energy diffuses through ejecta with a constant gray opacity (κ). The free parameters are the ejecta mass, M_{ej} , the ^{56}Ni mass fraction, f_{Ni} , the ejecta velocity, v_{ej} , the gamma-ray opacity, κ_{γ} , the temperature floor, T_{floor} , and the host extinction, A_V .

In particular, the raw radioactive decay luminosity is processed through the semianalytic diffusion solution (W. D. Arnett 1982; P. A. Pinto & R. G. Eastman 2000). We also compute the characteristic photon diffusion timescale,

$$\tau_m^2 = \frac{2\kappa_{\text{opt}} M_{\text{ej}}}{\beta c v_{\text{sc}}}, \quad (13)$$

where $\beta \simeq 13.8$ is the diffusion constant, and v_{sc} is the characteristic ejecta velocity. γ -ray leakage is controlled by κ_{γ} . The model assumes a single characteristic v_{ej} and homologous expansion, and a single zone of material.

To reproduce SN 2026gzf's fast rise and luminous peak at fixed κ , a fit to the light curve requires either a low effective diffusion mass, a high v_{ej} , or a high fraction of radioactive material. Nevertheless, the one-zone model provides a valuable benchmark for comparison to population studies of SNe (e.g., Z. Cano et al. 2017a; F. Taddia et al. 2019; G. P. Srinivasaragavan et al. 2024) and for providing estimates of the explosion properties from the light curve.

Applying the model to SN 2026gzf, we find that the one-zone model cannot reproduce the rapid optical rise without pushing to an unphysical radioactive composition. The posterior gives $M_{\text{ej}} = 0.48 \pm 0.01 M_{\odot}$ and $f_{\text{Ni}} = 0.991^{+0.007}_{-0.014}$, corresponding to $M_{\text{Ni}} = 0.473 \pm 0.012 M_{\odot}$. Although the resulting kinetic energy is not extreme, $E_K \simeq 2.6 \times 10^{51} \text{ erg}$, the inferred ejecta would be almost entirely ^{56}Ni . This is not physically plausible for a Type Ic-BL SN. The Bayesian evidence is also the lowest of the models considered ($\ln Z = -304.7$). Thus, we disfavor the one-zone model on both physical and statistical grounds.

4.4.2. ^{56}Ni Mixing Model

The failure of the one-zone model and SN 2026gzf's fast and bright rise naturally motivate a model in which a fraction of the radioactive material is mixed into the outer ejecta. Such mixing is supported by numerical simulations (e.g., D. K. Khatami & D. N. Kasen 2019; M. Reichert et al. 2023), and may naturally occur in some Type Ic-BL due to jet-driven turbulence (J. J. Grimmer et al. 2021; M. Reichert et al. 2023). We utilize the ^{56}Ni mixing model (N. Sarin 2026) in REDBACK. In addition to the parameters employed in the Arnett-like model (Section 4.4.1), the ^{56}Ni mixing model assumes that the ejecta-mass distribution follows a radial power law, with ^{56}Ni deposited in layers up to the free parameter f_{mix} , as well as a temperature-dependent κ parameterization designed to follow results from numerical simulations (A. P. Nagy 2018). The model divides the ejecta into velocity shells and deposits the ^{56}Ni into the inner fraction of the ejecta specified by f_{mix} ; larger values place radioactive material into faster, lower optical-depth layers. The default ejecta profile is a broken power law with a shallow inner density slope and a steep outer density slope. Each shell is evolved with radioactive heating, γ -ray leakage, adiabatic losses, and a local diffusion time before the shell luminosities are summed. Though semianalytic, this model captures the key physical effect missing from the one-zone model; radioactive heating can emerge earlier if some ^{56}Ni is mixed outward.

The mixing model provides a substantially better description of the data than the one-zone model, with $\ln Z = -125.7$. The inferred ejecta parameters are also reasonable for a SESNe explosion: $M_{\text{ej}} = 1.11^{+0.63}_{-0.23} M_{\odot}$, $E_{\text{SN}} = 4.39^{+2.50}_{-0.90} \times 10^{51} \text{ erg}$,

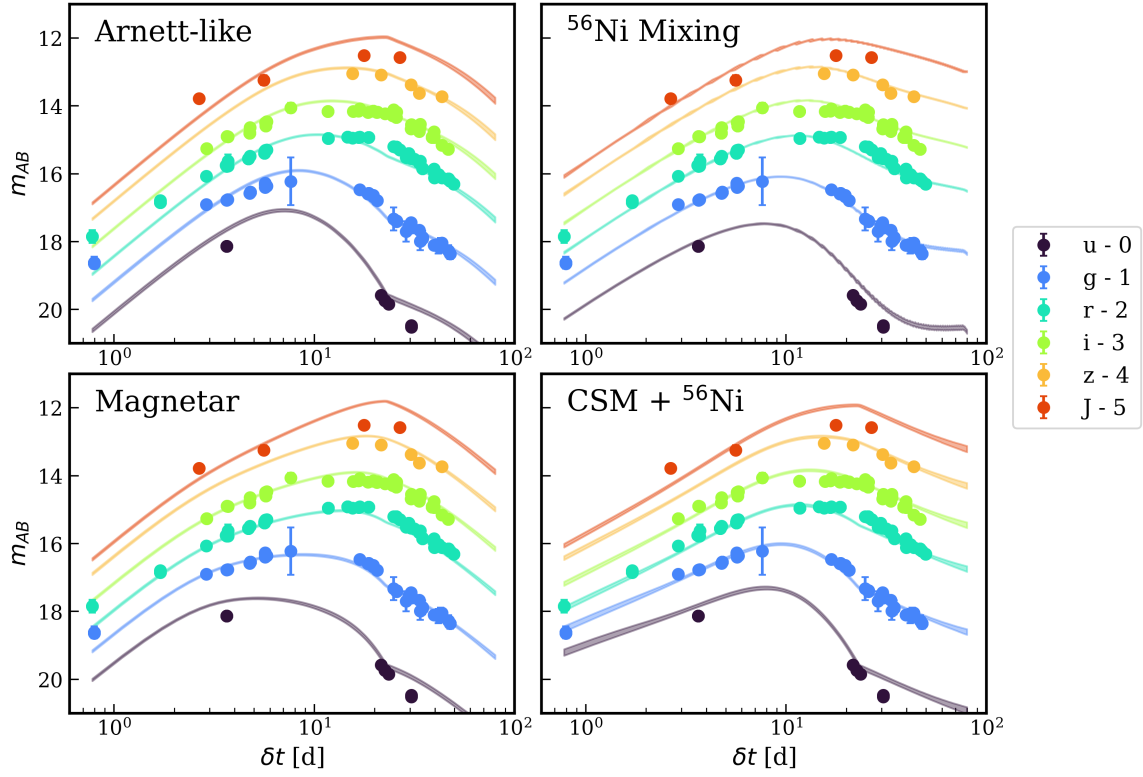


Figure 9. We fit the *ugrizJ*-band light curves of SN 2026gzf with five models in REDBACK (the pure CSM interaction model is not shown here as it requires infeasible M_{ej} and E_K ; Section 4.4.4). We disfavor the one-zone Arnett-like, magnetar, and pure CSM interaction models because they either provide poor statistical fits or require nonphysical parameters (Sections 4.4.1, 4.4.3, and 4.4.4). The combined CSM+ ^{56}Ni model is our preferred model. Relative to the ^{56}Ni mixing model, the constrained CSM+ ^{56}Ni fit improves the Bayesian evidence by $\Delta \ln Z \simeq 47$.

and $M_{\text{Ni}} = 0.398^{+0.005}_{-0.004} M_{\odot}$. The model prefers strong mixing, $f_{\text{mix}} = 0.80^{+0.11}_{-0.13}$, consistent with SN 2026gzf’s rapid rise, and overall captures the light-curve evolution. However, the model fails to fully account for the early blue/UV data, which could be indicative of a failure of our blackbody SED assumption.

4.4.3. Magnetar Model

We also fit the light curve with a generalized magnetar model (N. Sarin et al. 2022; C. M. B. Omand & N. Sarin 2024) implemented in REDBACK. This model injects magnetar spin-down power into the ejecta and diffuses the resulting luminosity through an expanding photosphere. Critically, this model captures the coupling between the magnetar spin-down energy and the dynamical evolution of the ejecta, a robust outcome of simulations (A. Suzuki & K. Maeda 2021) that dramatically alters the predictions of magnetar-driven SNe (C. M. B. Omand & N. Sarin 2024). The free engine parameters are the initial spin-down luminosity, L_0 , the spin-down timescale, t_{sd} , and the braking index, n , which could be fixed to $n = 3$ if one assumes that the magnetar only spins down due to vacuum dipole radiation (J. P. Ostriker & J. E. Gunn 1969). We sample with broad uninformative priors on all parameters but impose $M_{\text{ej}} > 0.1 M_{\odot}$ to avoid solutions that are nonphysical for a Type Ic-BL SN.

The magnetar model is statistically viable and outperforms the ^{56}Ni mixing model, with $\ln Z = -104.3$. However, the posterior is pinned to the lower ejecta-mass boundary, $M_{\text{ej}} = 0.101 M_{\odot}$, with a 90% credible interval of

$0.100\text{--}0.104 M_{\odot}$, and has a very short effective diffusion time, $\tau_m \simeq 1.8$ days. The inferred characteristic velocity is $v_{\text{ej}} \simeq 2.7 \times 10^4 \text{ km s}^{-1}$, while the magnetar engine has $L_0 \simeq 1.1 \times 10^{43} \text{ erg s}^{-1}$ and a broad spin-down timescale posterior centered at $t_{\text{sd}} \sim 1.6 \times 10^3$ days. We note that the braking index is essentially unconstrained (largely by the lack of late-time data that provides a constraint on this quantity), but assuming $n = 3$, our parameters would imply a magnetar with an initial spin period of $p_0 \sim 4$ ms and a magnetic field of $B_p \sim 2 \times 10^{13}$ G, which are not similar to the typical properties for putative magnetar’s in Type Ic-BL SNe (J.-P. Zhu & B. Zhang 2026). Therefore, although the magnetar model can provide a good fit to the data, it requires an extremely low effective ejecta mass and unusual birth properties. Thus, we disfavor the magnetar model on physical grounds.

4.4.4. CSM Interaction Model

We next fit a model powered purely by interaction between the SN ejecta and a shell of CSM. The implementation follows the semianalytic CSM interaction formalism of previous works (E. Chatzopoulos et al. 2013; V. A. Villar et al. 2017; B. Jiang et al. 2020), as implemented in REDBACK.

The model assumes homologously expanding ejecta with a broken power-law density profile interacting with a spherical CSM density profile $\rho_{\text{CSM}} = qr^{-s}$, where $q = \rho r_0^s$. The forward and reverse shock luminosities are computed from the analytic self-similar solution with a constant efficiency in

converting kinetic energy to thermal radiation, which we fix to 0.5. The free parameters are M_{ej} , v_{ej} , T_{floor} , A_V , the CSM mass, M_{CSM} , the density normalization, ρ , the inner radius of the CSM shell, r_0 , and the CSM density-profile index, s . The total CSM mass, M_{CSM} , together with r_0 , ρ , and s , sets the outer radius of the shell. The CSM is assumed to be static, i.e., $v_{\text{CSM}} \ll v_{\text{ej}}$, such that the dynamical evolution of the CSM can be ignored. Outside of the interval $r_0 \leq R \leq r_{\text{out}}$, the CSM density is set to zero. The diffusion calculation depends most directly on the optically thick CSM mass, where we define the mass exterior to the CSM photosphere as characterized by $\kappa > 2/3$. Thus M_{CSM} and the outer radius are typically weakly constrained unless the SN ejecta have fully traversed the shell.

Sampling with broad uninformative priors, we find that an unconstrained pure CSM model can reproduce much of the light-curve shape ($\ln Z = -118.2$), but only by requiring an implausibly massive and energetic ejecta component: $M_{\text{ej}} = 26.4^{+2.5}_{-4.3} M_{\odot}$ and $E_K \simeq 1.1 \times 10^{53}$ erg. This is inconsistent with expectations for a Type Ic-BL SN. Imposing stricter constraints on the ejecta mass and additionally physical constraints such that the CSM photosphere lies within the shell and the diffusion time is shorter than the shock-crossing time, the pure CSM fit cannot accommodate both the late-time brightness and the late-time decay, resulting in a poor fit to the data ($\ln Z = -292.8$). The combination of infeasible parameters and physical inconsistency disfavors a pure interaction-powered model.

4.4.5. CSM Interaction and ^{56}Ni Model

Finally, we fit a model that combines CSM interaction with the single-zone radioactive ^{56}Ni heating. This model uses the same CSM interaction engine described above, while adding a ^{56}Ni - ^{56}Co decay component diffusing through the ejecta and optically thick CSM. We sample with broad uninformative priors but impose the physical constraints of shock-crossing time and photosphere location as described in Section 4.4.4.

This model provides the strongest physically interpretable fit among the models considered, with $\ln Z = -78.7$. It is favored over the magnetar model by $\Delta \ln Z \simeq 26$, over the ^{56}Ni mixing model by $\Delta \ln Z \simeq 47$, and over the one-zone model by $\Delta \ln Z \simeq 226$. Relaxing the physical constraint gives a higher fit, but places the CSM at much larger radii and violates the self-consistency conditions of the interaction model; we therefore use the result with a constrained prior for our physical interpretation.

Our inferred values are $M_{\text{ej}} = 1.05^{+0.12}_{-0.12} M_{\odot}$, $f_{\text{Ni}} = 0.303^{+0.046}_{-0.036}$, corresponding to $M_{\text{Ni}} = 0.318^{+0.015}_{-0.013} M_{\odot}$. The kinetic energy is $E_K = (6.30^{+0.87}_{-0.85}) \times 10^{51}$ erg, corresponding to a characteristic ejecta velocity of $v_{\text{ej}} \simeq 2.45 \times 10^4 \text{ km s}^{-1}$. These parameters are all consistent with expectations of Type Ic-BL SNe.

The CSM component is compact compared with typical late-time interaction systems but more extended than the radius one may expect from a stripped, compact star. The fit gives $r_0 = 4.39^{+5.07}_{-2.63} \text{ AU}$ or $(6.56^{+7.58}_{-3.93}) \times 10^{13} \text{ cm}$ for the inner edge of the CSM shell with a density of $\rho = (4.45^{+20.2}_{-3.39}) \times 10^{-13} \text{ g cm}^{-3}$, and a nearly wind-like density profile, $s = 1.98^{+0.02}_{-0.03}$. The total CSM mass is not tightly constrained due to our short observing window, but we infer $M_{\text{CSM}} = 0.029^{+0.605}_{-0.027} M_{\odot}$ at 68% credibility. The optically thick mass participating directly in the diffusion problem is much

smaller, $M_{\text{CSM,thick}} \simeq 1.1 \times 10^{-3} M_{\odot}$, and the CSM photosphere lies at $R_{\text{ph,CSM}} \simeq 11.7 \text{ au}$. As mentioned, the inferred outer CSM radius is broad, with a median of $\sim 150 \text{ au}$, reflecting the weak leverage of the optical light curve on low-density material at large radii.

4.4.6. Comparison of Inferred Explosion Properties

In Figure 7, we compare the inferred explosion properties for the CSM + ^{56}Ni model to those of other Type Ic-BL, FXT, and GRB SNe (Z. Cano et al. 2017a; G. P. Srinivasaragavan et al. 2024). These comparison values are mostly derived using one-zone Arnett models; therefore, our comparison is not strictly model-independent, though the presence of CSM at large radii is rarely seen. Nevertheless, SN 2026gzf lies within the broad range of M_{ej} , M_{Ni} , and E_K inferred for Type Ic-BL SNe.

For the fiducial CSM+ ^{56}Ni model, we find $\tau_m \simeq 6.2$ days. Thus, although the total time from explosion to maximum light is not exceptionally short, the inferred diffusion time is among the shorter values for SESNe (Figure 7). This is consistent with the main conclusion of the model comparison; the early light curve cannot be explained by a centrally concentrated one-zone ^{56}Ni model alone, and requires either extensive outward mixing of the radioactive material (Section 4.4.2) or an additional early heating component (Section 4.4.5). Among the models tested here, the combination of ^{56}Ni heating and CSM interaction provides the most compelling explanation.

5. Environmental Analysis

5.1. Global Host-galaxy Properties

We next present a detailed analysis of the host galaxy of SN 2026gzf, SDSS J095942.88+002506.2 using public photometry and spectroscopy as well as the Python-based stellar population modeling inference code *Prospector* (J. Leja et al. 2019; B. D. Johnson et al. 2021). We describe the details of our analysis in Appendix Section A.4.

For easy interpretation of the *Prospector* results, we calculate physical properties from the sampled values. For example, we determine a stellar mass (M_*), mass-weighted stellar population age (t_m), and present-day (0–100 Myr) SFR and specific SFR ($\text{sSFR} = \text{SFR}/M_*$) using the SFH and M_F . We also convert the amount of light attenuated from young ($\tau_{V,1}$) and old ($\tau_{V,2}$) stars to a total V-band magnitude by multiplying their sum by 1.086. In Table 2, we list the medians and 68% confidence intervals of these properties.

EP 260321a's host is a young ($t_m = 3.12 \text{ Gyr}$) dwarf galaxy ($M_* = 10^{8.55} M_{\odot}$), with a moderate amount of star formation ($\text{SFR} = 0.06 M_{\odot} \text{ yr}^{-1}$, $\log(\text{sSFR}) = -9.8 \text{ yr}^{-1}$). We further determine that the host has subsolar stellar ($\log(Z_*/Z_{\odot}) = -1.84$) and gas-phase ($\log(Z_{\text{gas}}/Z_{\odot}) = -0.63$) metallicities. In addition to the *Prospector*-determined metallicities, we compute a gas-phase oxygen abundance ($12 + \log(\text{O}/\text{H})$). Flux measurements and uncertainties for the observed [O II], [O III], and $H\beta$ lines are provided by DESI, along with uncertainties. We use the C. A. Tremonti et al. (2004) R23-calibration method to determine $12 + \log(\text{O}/\text{H})$, where $\text{R23} = \log_{10}([\text{O II}] + [\text{O III}]) / H\beta$. To incorporate the uncertainties into this measurement, we sample 1000 fluxes for each line from a Gaussian distribution and calculate 1000 $12 + \log(\text{O}/\text{H})$ values for the host. We place the median and 68% confidence interval in Table 2 and determine that the host has a slightly subsolar $12 + \log(\text{O}/\text{H})$ metallicity of $= 8.61$.

Table 2
Host-galaxy Stellar Population Properties

GLOBAL	
$\log(M_*/M_\odot)$	$8.55^{+0.06}_{-0.06}$
$\text{SFR} (M_\odot \text{ yr}^{-1})$	$0.06^{+0.04}_{-0.02}$
$\log(\text{sSFR}) (\text{yr}^{-1})$	$-9.8^{+0.22}_{-0.21}$
$t_m (\text{Gyr})$	$3.12^{+2.72}_{-1.32}$
$\log(Z_*/Z_\odot)$	$-1.84^{+0.18}_{-0.12}$
$\log(Z_{\text{gas}}/Z_\odot)$	$-0.63^{+0.09}_{-0.06}$
$A_V (\text{mag})$	$0.09^{+0.07}_{-0.05}$
$12 + \log(\text{O}/\text{H})$	$8.61^{+0.1}_{-0.12}$
KNOT	
$\log(M_*/M_\odot)$	$6.97^{+0.94}_{-0.07}$
$\text{SFR} (M_\odot \text{ yr}^{-1})$	$0.16^{+0.05}_{-0.06}$
$\log(\text{sSFR}) (\text{yr}^{-1})$	$-7.85^{+0.19}_{-0.9}$
$t_m (\text{Gyr})$	$1.69^{+3.37}_{-1.56}$
$A_V (\text{mag})$	$0.43^{+0.21}_{-0.15}$

Note. Our derived stellar population properties (median and 68% confidence intervals) for the host galaxy of SN 2026gzf and the star-forming knot within the host.

To further contextualize these results, we compare them to the host galaxies of long GRBs, optically discovered Types Ic-BL, Ib/c, and II SNe. We gather host stellar masses and sSFRs for spectroscopically classified Type Ic-BL, Ibc, and II SNe at $z < 0.2$ in A. E. Nugent et al. (2026), which were modeled with a nearly identical *Prospector* template as discussed here. We collect host $12+\log(\text{O}/\text{H})$ metallicities for these populations in Y.-J. Qin & A. Zabludoff (2024). We obtain long GRB host stellar masses and sSFRs from K. M. Svensson et al. (2010), D. A. Perley & R. A. Perley (2013), F. Y. Wang & Z. G. Dai (2014), Y. Niino et al. (2017), and $12+\log(\text{O}/\text{H})$ metallicities from F. Y. Wang & Z. G. Dai (2014), and limit this sample to $z < 0.5$ to be in a more comparable redshift range to the other host populations. We show cumulative distributions (CDFs) of the host stellar masses, sSFRs, and $12+\log(\text{O}/\text{H})$ metallicities in Figure 10. We find that the host of SN 2026gzf falls in the bottom 32% of stellar masses for long GRB hosts, and the bottom 10% for Type Ic-BL, Ibc, and II hosts. On the other hand, the host of SN 2026gzf has a more typical sSFR when compared to the long GRB and Type Ic-BL host populations, falling in the bottom 32% and 60% of sSFRs, respectively. The host sSFR is much higher than observed for typical CCSN hosts, falling in the top 23% of sSFRs for Type II SN hosts and 17% for Type Ibc SN hosts. Finally, the host metallicity is much lower than observed from Type II (bottom 18%) and Ibc (bottom 8%) hosts, but more typical for long GRB (bottom 81%) and Type Ic-BL (bottom 30%) hosts. In summary, we find that the EP 260321a's host is comparable to both long GRB and optically discovered Type Ic-BL SNe, though its properties are moderately more consistent with those of long GRBs.

5.2. Stellar Population Modeling of SN 2026gzf's Underlying Blue Knot

We also perform a simplistic environmental analysis of the blue knot consistent with the location and redshift of SN 2026gzf. We obtain aperture photometry of the knot from

DECaLS DR10 and list the photometric measurements in Table 3. To determine its stellar population properties, we model the photometry with the same *Prospector* model discussed in Section 5.1, without the parameters used to fit a spectrum. As we only fit four bands of optical photometry, the star formation and stellar mass are the only parameters we consider to be robustly constrained. We present our stellar population modeling results of the knot in Table 5.1. Due to the width ($\sim 1''$) and orientation of the slit used in our SN spectra, it is possible that light from both the blue knot and broader galaxy is contributing to the observed emission lines. Thus, we do not use the galaxy emission lines observed in our SN spectra in our analysis.

The properties of this knot appear to be consistent with an H II region. We determine that the knot has $M_* = 10^{6.97} M_\odot$, $\text{SFR} = 0.16 M_\odot \text{ yr}^{-1}$, and $\log(\text{sSFR}) = -7.85 \text{ yr}^{-1}$. The knot's SFH appears to be clearly rising with a rapid increase in SFR in the past 30 Myr, suggestive of a recent burst of star formation and potentially indicative that the knot is an H II region. The SFR and SFH history are consistent with those of the central region of the massive H II region, 30 Doradus in the Large Magellanic Cloud (e.g., M. Cignoni et al. 2015).

Overall, we conclude that SN 2026gzf was born in or nearby an exceptionally star-forming environment. In comparison to the global host properties of SN 2026gzf, the knot's sSFR is greater by ~ 2 orders of magnitude. Moreover, as shown in Figure 10, the knot has much higher sSFR than the global properties of the long GRB, Type Ic-BL, Ibc, and II host populations: falling in the 99% of sSFR for the SN hosts, and the 94% for long GRB hosts. However, we note that such local environment studies are not possible for the majority of SESNe host galaxies and thus direct comparison of the knot with the global host properties is discouraged.

5.3. Estimate of SFR from Radio Observations

Finally, we estimate a lower limit on the host-galaxy SFR required to account for the observed radio emission, using the measured integrated flux density and the following relation E. J. Murphy et al. (2011):

$$\left(\frac{\text{SFR}_{6.2 \text{ GHz}}}{M_\odot \text{ yr}^{-1}} \right) = 6.35 \times 10^{-29} \left(\frac{L_{6.2 \text{ GHz}}}{\text{erg s}^{-1} \text{ Hz}^{-1}} \right). \quad (14)$$

From this, we calculate an SFR of $\approx 0.037 M_\odot \text{ yr}^{-1}$ from our radio observations. This is a factor of ~ 4 below the SFR inferred for the knot from optical imaging (Table 2). However, as the VLA detection is marginal ($\lesssim 5\sigma$), we estimate a large uncertainty on the radio SFR. Future, deeper VLA imaging and further high-resolution optical observation of the star-forming knot are necessary to constrain the amount of dust obscuration in the knot.

6. Discussion

6.1. Combined Progenitor Picture

In Sections 3–5, we leverage X-ray, optical, and radio observations of EP 260321a/SN 2026gzf to obtain independent constraints on the progenitor and CSM in its immediate environment. Here, we summarize our constraints and discuss the broader picture we may infer from our multiwavelength constraints.

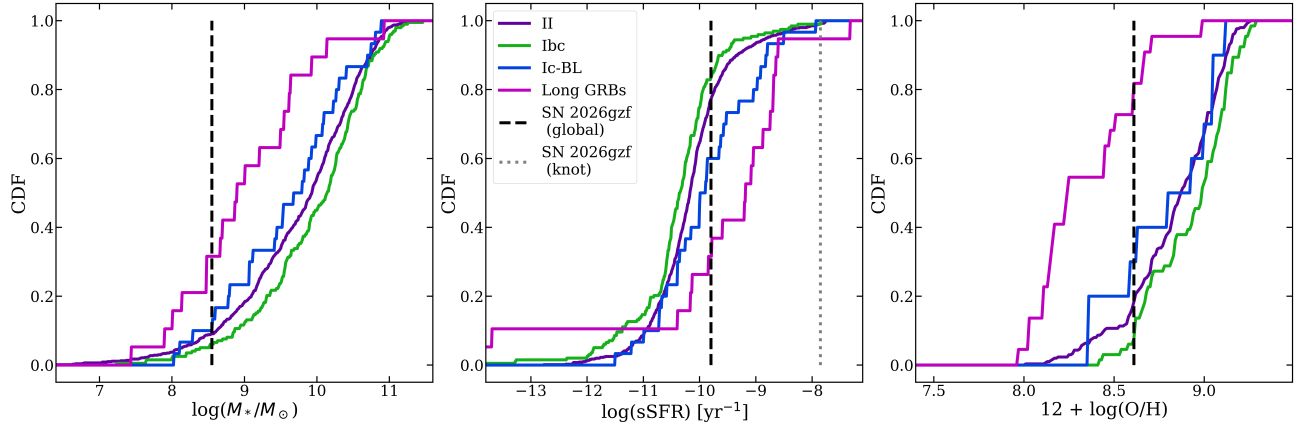


Figure 10. The global host-galaxy stellar mass (M_* ; left), sSFR (middle), and $12 + \log(\text{O}/\text{H})$ metallicity (right) of SN 2026gzf (black dashed line) compared to the respective CDFs of the hosts of long GRBs (magenta; K. M. Svensson et al. 2010; D. A. Perley & R. A. Perley 2013; F. Y. Wang & Z. G. Dai 2014; Y. Niino et al. 2017), Type Ic-BL (blue), Ibc (green), and II (dark purple) SNe (Y.-J. Qin & A. Zabludoff 2024; A. E. Nugent et al. 2026). We also show the sSFR of the star-forming knot coincident with the location of SN 2026gzf (gray dotted line). The host itself is low mass, low metallicity, and star-forming, with properties that are overall more typical for long GRB hosts than the other transient host populations. The knot is extremely star-forming in comparison to the global host properties and other transient host populations.

Table 3
Host-galaxy Photometry

Filter	AB mag
GLOBAL	
GALEX FUV	19.45 ± 0.11
GALEX NUV	19.63 ± 0.03
DECaLS g	18.23 ± 0.01
DECaLS r	18.10 ± 0.01
DECaLS z	18.14 ± 0.02
Pan-STARRS g	18.36 ± 0.01
Pan-STARRS r	18.18 ± 0.01
Pan-STARRS i	18.18 ± 0.02
Pan-STARRS z	18.16 ± 0.02
Pan-STARRS y	18.21 ± 0.05
2MASS J	18.47 ± 0.03
WISE $w1$	19.50 ± 0.17
WISE $w2$	19.84 ± 0.29
WISE $w3$	17.61 ± 0.58
WISE $w4$	15.93 ± 1.10
KNOT	
DECaLS g	18.697 ± 0.002
DECaLS r	19.015 ± 0.002
DECaLS i	19.492 ± 0.003
DECaLS z	19.447 ± 0.004

Note. Photometry of the host of SN 2026gzf and the star-forming knot it is coincident with, used in the *Prospector* stellar population modeling fit. We note that the host was not detected in 2MASS H and K ; hence they were not included in the fit.

Our preferred optical model combines CSM interaction with ^{56}Ni radioactive heating. The model favors a CSM inner radius $r_0 = 4.4^{+5.1}_{-2.6}$ au ($6.6^{+7.6}_{-3.9} \times 10^{13}$ cm) and a nearly wind-like density profile, $s \simeq 2$. The total CSM mass is poorly constrained, $M_{\text{CSM}} = 0.029^{+0.605}_{-0.027} M_{\odot}$, due to the absence of late-time data in the optical light curve but may be improved with further monitoring. The inferred optically thick CSM mass is much smaller, $M_{\text{CSM,thick}} \sim 10^{-3} M_{\odot}$, with a CSM

photospheric radius of ~ 12 au and a broad outer-radius posterior with a median of ~ 150 au.

The X-ray constraints probe a smaller radial scale compared to the optical. The analytic SBO calculation gives $R_e \sim 2.1\text{--}5.0 \times 10^{12}$ cm (0.14–0.33 au) and $M_e \sim (0.2\text{--}6) \times 10^{-6} M_{\odot}$. This radius is comparable to the outer scale of an inflated Wolf–Rayet envelope (e.g., J. H. Shiode & E. Quataert 2014) and is well inside the characteristic optical CSM radius (Figure 11). The REDBACK X-ray fit also supports a compact, rapidly fading breakout-like component, with an effective emitting radius that is small compared with the optical CSM scale, although the sparse X-ray data do not determine the geometry. We therefore interpret the X-rays and optical emission as likely probing different radial zones; the X-rays originate from SBO through a compact stellar envelope or very nearby low-mass material, while the optical light curve is shaped by interaction with more extended material at radii of several astronomical units and beyond (Figure 11).

There are several caveats to this interpretation. For example, if the CSM probed by the optical emission was a smooth, spherical, optically thick structure overlying the compact X-ray breakout region, the soft X-rays would likely be absorbed and reprocessed. The apparent difference between the X-ray and optical radii may then provide evidence for a nonspherical or porous CSM geometry, clumping, or a line of sight through which the compact breakout emission can escape. The difference in radii could also be pointing toward limitations in modeling, such as a more structured CSM that departs from a power law as enforced by the optical model (Section 4.4.5) or asymmetries in the CSM distribution, which would change our inferred parameters and, by extension, constraints on the CSM. Both of these would likely require further detailed modeling with more flexible and self-consistent models jointly on the full X-ray and optical dataset (e.g., N. Sarin & R. Hirai 2026).

The radio limits add an important constraint on the density at larger radii. For fast ($\beta = 0.10\text{--}0.36$; 90% confidence interval) SN ejecta interacting with a wind-like CSM and assuming $\epsilon_e = \epsilon_B = 0.1$ (Section 3.3), the radio nondetections

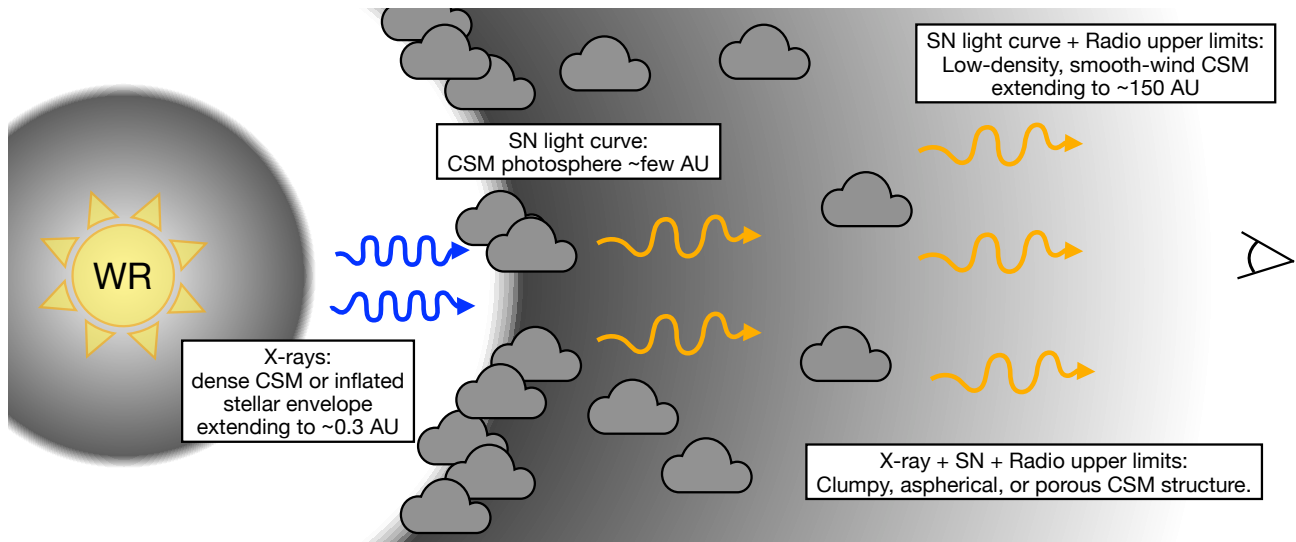


Figure 11. Cartoon diagram of the CSM orientations favored by our multiwavelength constraints on EP 260321a/SN 2026gzf. Our analysis favors two distinct regions of CSM that produce the X-ray (inner region) and SN light curve (outer region). Further, we favor an outer CSM structure that is clumpy, aspherical, porous, and/or characterized by a steep density drop outside the region probed through the SN light curve.

imply a low mass-loading parameter,

$$\log_{10} \left[\frac{\dot{M}/v_w}{M_{\odot} \text{ yr}^{-1}/(\text{km s}^{-1})} \right] \leq -7.92, \quad (15)$$

with even lower mass loading required for the fastest ejecta. For a Wolf-Rayet-like wind velocity of $v_w = 1000 \text{ km s}^{-1}$, this corresponds to $\dot{M} \sim 1.2 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$. Expressed as a smooth-wind equivalent mass, this mass loading corresponds to only $\sim 1.7 \times 10^{-6} M_{\odot}$ within 30 au and $\sim 8 \times 10^{-6} M_{\odot}$ within 150 au. These values are well below the median total CSM mass inferred from the optical model but are still consistent, especially considering the different modeling assumptions, such as the spherical, static, power-law CSM enforced by the optical model. The radio data argue against a dense, smooth, spherically symmetric wind extending to large radii. The CSM is more likely to be radially confined, clumpy, asymmetric, or characterized by a steep density drop outside the region probed by the SN light curve.

The host-galaxy environment is consistent with this picture. EP 260321a occurred in a low-mass, subsolar-metallicity, star-forming dwarf galaxy, with global properties more similar to the hosts of long GRBs than those of optically discovered SESNe (Section 4). This is a potential indicator that the core-collapse of EP 260321a’s progenitor produced some jet emission, as stars in lower metallicity environments retain greater angular momentum as they evolve (A. Heger et al. 2003). Either a weak ($E_{\text{k,iso}} \lesssim 10^{49} \text{ erg}$) or off-axis jet could be the source of the shock which created EP 260321a. However, we caution that the global host properties inferred in our environmental analysis are several orders of magnitude greater than probed by the shock. EP 260321a’s X-ray and radio properties do not appear compatible with an on-axis jet origin (e.g., Section 3). Longer-term radio monitoring is key to searching for emission from an off-axis jet (e.g., A. Corsi et al. 2016; J. K. Leung et al. 2023; G. Schroeder et al. 2025; T. O’Dwyer et al. 2026).

Overall, our favored progenitor picture is a compact Wolf-Rayet-like star that underwent enhanced mass loss before explosion, producing a small amount of nearby material responsible for the X-ray breakout and additional extended, structured CSM that shaped the early optical light curve. The mass loss need not resemble a steady, smooth wind. Instead, the combined optical, X-ray, and radio constraints could be pointing toward a radially structured or asymmetric CSM configuration: compact low-mass material at $\lesssim 0.3 \text{ au}$ (producing the X-rays), CSM beginning at a few astronomical units (affecting the optical light curve), and relatively low smooth-wind density at larger radii (probed through the radio; Figure 11). A greater sample of events with early X-ray detections, dense optical follow-up, and late-time radio monitoring will be required to determine whether this CSM was produced by eruptive pre-SN mass loss, binary interaction, or the final stages of Wolf-Rayet wind evolution.

6.2. Rates of EP 260321a-like SBO Events

While EP 260321a-like X-ray signals are rarely detected, its optical counterpart, SN 2026gzf, is not unusual when compared to the Type Ic-BL SNe regularly detected by optical surveys (Figure 7; F. Taddia et al. 2019; G. P. Srinivasaragavan et al. 2024). We are thus motivated to consider: Are the rates of optically discovered Type Ic-BL SNe consistent with EP’s detection rate of X-ray SBOs? We limit our calculation to Type Ic-BL SNe, though we note that XRF 080109’s counterpart, SN 2008D, was a Type Ib SN, for which the observed rate in optical surveys is higher (e.g., D. A. Perley et al. 2020).

To determine an expected rate of X-ray SBO produced by Type Ic-BL SNe, we employ an optically discovered Type Ic-BL SNe rate confidence interval of $800\text{--}3000 \text{ Gpc}^{-3} \text{ yr}^{-1}$ (D. A. Perley et al. 2026, in preparation) from the ZTF Bright Transient Survey (BTS; D. A. Perley et al. 2020). This interval is drawn from integrating over the rates of Type Ic-BL SNe in peak magnitude bins brighter than $M_r > -16 \text{ mag}$, encapsulating all Type Ic-BL’s in the ZTF BTS (e.g., Figure 6; G. P. Srinivasaragavan et al. 2024). We next assume

WXT reaches a limiting flux of $3 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$ in its all-sky survey exposures (H. Cheng et al. 2025), and observes 9.3% of the sky instantaneously with a 100% duty cycle. Finally, we make the assumption that all FXTs from Type Ic-BL SNe SBO will reach the same peak luminosity as EP 260321a, $L_{0.5-4 \text{ keV}} = 2.2 \times 10^{44} \text{ erg s}^{-1}$ (Q. J. Huang et al. 2026a). Under these assumptions, we derive the horizon at which WXT will observe EP 260321a-like FXTs of $d_L = 247 \text{ Mpc}$ or $z = 0.054$. Incorporating EP's sky fraction and the range of BTS Type Ic-BL SN rates results in an observed rate of 4.4–16 yr^{-1} .

We next evaluate whether this range is compatible with EP's detection rate. EP was launched in 2024 January and completed commissioning in 2024 July. Considering up to the present day (2026 May), EP's survey duration is $\sim 1.8 \text{ yr}$, within which one EP SBO has been discovered. Invoking Poisson statistics gives a 90% (95%) confidence interval of the observed EP SBO rate of 3×10^{-3} –4.0 (10^{-3} –4.8) yr^{-1} . EP observations are thus consistent with the lower range of rates we infer from the BTS Type Ic-BL SNe sample at the 95% confidence level but not at the 90% level. Our analysis indicates some evidence that not all Type Ic-BL SNe produce EP 260321a-like FXTs. However, we cannot confidently eliminate the possibility at present.

There are several potential factors that would lead to a lower rate inferred from EP than BTS Type Ic-BL SNe. First, there are likely systematic effects that would lead to a lower observed EP rate, including detections being interrupted by slewing, a duty cycle $< 100\%$, or low signal-to-noise ratios preventing robust X-ray spectral constraints for events at the edge of the redshift threshold. Second, it is possible and indeed likely that not all Type Ic-BLs create luminous SBOs given the expected diversity in mass-loss histories and explosion properties (e.g., C. L. Fryer et al. 2026). Whether the SN brightness and the FXT brightness are correlated remains observationally undetermined, but is supported by the two observed SBOs; the SBO XRF 080109 was a factor of ~ 3 less luminous in X-rays compared to EP 260321a, and SN 2008D's peak brightness was ~ 10 times less luminous compared to SN 2026gzf. SN 2026gzf's peak magnitude is brighter than 75% of optically discovered Type Ic-BL SNe (Section 4.1), which themselves may not be representative due to Malmquist bias (F. Taddia et al. 2019; G. P. Srinivasaragavan et al. 2024). If a correlation between FXT and SN luminosity exists, this would indicate most SBOs from Type Ic-BL SNe are less luminous than EP 260321a. A larger sample of SBO events is required to constrain the diversity of observed SBO signals, their correlations with SN properties, and the rates of such events.

7. Conclusion

We have presented our comprehensive optical and radio observations of the counterpart to EP's first SBO FXT: EP 260321a. Our main conclusions are as follows:

1. Analytic arguments and Redback modeling of EP 260321a favor an SBO origin for the X-ray emission, representing the first X-ray SBO detected by EP.
2. Our radio upper limits rule out an on-axis jet of $E_{\text{iso}} \gtrsim 10^{49} \text{ erg}$ for $n > 10^{-2} \text{ cm}^{-3}$ and $\epsilon_e = \epsilon_B = 0.1$.

- Further, the radio places deep constraints on CSM at larger radii, favoring modest mass loading at larger radii.
3. EP 260321a was accompanied by a Type Ic-BL SN, SN 2026gzf, at $z = 0.0343$, rendering it the most nearby EP FXT known to date and the first Type Ic-BL SN with an X-ray SBO counterpart.
4. SN 2026gzf's r -band light curve, expansion velocities, M_{ej} , M_{Ni} , and E_K are consistent with the ranges for both GRB SNe and optically discovered Type Ic-BL SNe.
5. SN 2026gzf rapidly rose in brightness until $\delta t \sim 1 \text{ week}$ ($\tau_m = 6.2 \text{ days}$). We show that this rapid rise cannot be explained solely with a one-zone SN model in which ^{56}Ni radioactive decay is concentrated in the center of the explosion. Of the five models we explore, a model that incorporates CSM interaction and ^{56}Ni radioactive decay is favored on both physical and statistical grounds.
6. SN 2026gzf's host-galaxy mass, sSFR, and $(12 + \log(\text{O}/\text{H}))$ metallicity are within the 95% confidence intervals of both GRB SNe hosts and optically discovered Type Ic-BL SNe hosts. The stellar mass and metallicity of SN 2026gzf's host are more compatible with the medians for GRB SNe.
7. Taken together, our observations and analysis favor a Wolf-Rayet progenitor star surrounded by either an inner region of dense CSM or an extended stellar envelope at $\sim 0.3 \text{ au}$. Our SN analysis also favors an additional CSM component beginning at $\sim 4 \text{ au}$, which is likely clumpy, aspherical, or otherwise porous.
8. The rates of EP SBO events are consistent at the 95% confidence level, but not the 90% confidence level, with the range of rates implied if all Type Ic-BL SNe produce similar signals to EP 260321a. Continued observations from EP will determine whether these rates remain consistent.

Our observations and analysis of EP 260321a and SN 2026gzf reveal significant insight into the circumstellar environment of a stripped-envelope, massive star just prior to collapse. The advent of the UV survey monitor, ULTRASAT (Y. Shvartzvald et al. 2024), which will be sensitive to spectrally softer SBO signals, along with continued observations from EP, promise significant opportunities for multiwavelength follow-up of SBO events in the coming decade.

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This Letter includes data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile.

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Appendix

A.1. Photometric Data Reduction

A.1.1. LSST Photometry Prior to EP 260321a

LSST first detected a transient at the location of SN 2026gzf on 2026 January 18 (LSST-AP-DO-314003014107006318), approximately 3 months prior to EP's detection of the SN. Repeated variability was detected from February 19–24. However, the faintness of the detections (all near LSST's single-exposure detection limit of ~ 25 th magnitude; Ž. Ivezić et al. 2019) and the clear dipole features in the difference imaging cast doubt on the interpretation that these were true SN precursors. We perform an independent analysis of the science images released with these LSST detections (LSST-AP-DS-314003014107006318 and LSST-AP-DS-170032901818679622 through 170265994707599374, downloaded from ALeRCE; F. Förster et al. 2021) using Scarlet2, a nonparametric forward-modeling code which makes use of machine learning priors and can model multiresolution images from different instruments, representing both static and variable sources (C. Ward et al. 2025; P. Melchior et al. 2026).

With Scarlet2, we extract a light curve of the transient source directly from the science images, independent of the host-galaxy light. We also fit a WCS shift between the science images when necessary, eliminating any coordinate offset issues. We force the flux of the transient source to be 0 in its dimmest epoch in each band (based on the LSST light curve provided on ALeRCE), allowing us to constrain whether the pre-SN detections are consistent with a single flux value (the value in the dimmest, "reference" epoch) or not. We find that all of the LSST transient alerts prior to the SN are consistent with no variation $\geq 5\sigma$ in g or r bands, and the vast majority are consistent with no variation $\geq 3\sigma$. The most significant change

in the r band is a 4.7σ detection of variability between the observation on MJD 61058.3 and the reference epoch on MJD 61095.2. The most significant change in the g band is a 4.4σ detection of variability between the observation on MJD 61094.2 and the reference epoch on MJD 61095.1. While we cannot confidently say precursors are detected for SN 2026gzf, this result shows the potential of LSST to identify SN precursor activity.

A.1.2. SEDm Imaging

We obtained *ugri*-band imaging with the Rainbow Camera mounted on the Palomar 60 inch telescope (PI: Ahumada). We reduced the data using the standard FPIPE imaging pipeline.

A.1.3. LT IO:O

LT observations were taken with the IO:O optical camera in the Sloan Digital Sky Survey (SDSS) *griz* filters. The exposures were reduced by the automatic LT pipeline; same filter exposures per epoch in each filter were then processed with custom image subtraction and photometry software⁴⁰ following methods described in (C. Fremling et al. 2016), utilizing the software *SWarp* (E. Bertin 2010), *SExtractor* (E. Bertin & S. Arnouts 1996), and *PSFex* (E. Bertin 2013), using reference images and calibration stars from Pan-STARRS-1 (K. C. Chambers et al. 2016, 2019).

A.1.4. WINTER

We observed ZTF26aaonmha/SN 2026gzf in the J and shortened H bands with the Wide-field Infrared Transient Explorer (WINTER; N. P. Lourie et al. 2020; D. Frostig et al. 2025), a camera mounted on the 1 m telescope at Palomar Observatory. Data were reduced using the standard WINTER pipeline built using *mirar* (R. D. Stein et al. 2025). Astrometric calibration was performed using Gaia positions (Gaia Collaboration 2021), while photometric calibration was performed using the Two Micron All-Sky Survey (2MASS; M. F. Skrutskie et al. 2006).

A.2. Spectroscopic Data Reduction

A.2.1. GMOS Spectra

We obtained GMOS spectra using the B480 grating at a central wavelength of 520 nm and a slit width of $1''$. We performed bias correction, flat-fielding, and wavelength calibration using DRAGONS (K. Labrie et al. 2019). We flux-calibrate our spectra using the standard star LTT6248 with DRAGONS.

A.2.2. NGPS Spectra

The Palomar 200 inch NGPS observation of ZTF26aaonmha/SN 2026gzf was carried out using a $1.5''$ slit width and a 900 s exposure time. The airmass was 1.29 at the time of observation. On-chip spatial binning was set to 2, and spectral binning was set to 3. Resolving power for this setup is $R \sim 1500$. Data were reduced following standard procedures for long-slit spectroscopic data reduction using a custom pipeline developed for NGPS. Wavelength calibration was performed against daytime ThAr and FeAr arc exposures. Flux calibration was performed

with an observation of the spectrophotometric standard Feige34 taken within a few hours of the science observation at airmass ≈ 1.0 .

A.2.3. Goodman Spectra

We obtained two epochs of long-slit spectroscopy of ZTF26aaonmha/SN 2026gzf with the Goodman High Throughput Spectrograph (GHTS; J. C. Clemens et al. 2004) mounted on the Southern Astrophysical Research (SOAR) telescope on 2026 April 22 and 2026 April 30. The observations consisted of 3×600 s exposures. Both observations were taken with a grating of 400 lines mm^{-1} and a $1''.0$ wide slit mask in the M1 spectroscopic setup (hereafter 400M1) with 2×2 binning using the GHTS Red Camera. The 400M1 spectra cover a wavelength range of 3800–7040 Å.

The spectra were reduced using *pypeit* (J. X. Prochaska et al. 2020a, 2020b), using arcs taken immediately before and/or after target observation and calibration images from the same night. Flux calibration was performed using standard stars observed on the night of the observations with an identical 400M1 setup and 2×2 binning.

A.2.4. FIRE Spectra

We obtained one epoch of spectroscopy with the FIRE spectrograph mounted on the Magellan Baade telescope. Observations were performed in the high-throughput prism mode ($R_j \sim 500$) using a $1''.0$ slit and high detector gain (1.3 e-/DN). We conducted 2.5 ABBA dither sequences with 137 s per exposure, using the Sample-Up-The-Ramp (SUTR) read-out mode.

The spectrum was reduced using FIREHose v2.0 (J. Gagné et al. 2015), a modified version of the IDL-based FIREHose pipeline, which relies on *spectool*.

A.3. Constraints from X-Ray and Radio Observations

We show the posterior light curves and/or corner plots from our REDBACK constraints on the properties of the shock inferred from the X-ray observations (Figure 12), the on-axis jet with $\epsilon_B = 0.1$ (Figure 13) and allowed to vary over $10^{-4} \leq \epsilon_B \leq 0.1$ (Figure 14), as well as on the wind mass-loss rate using the X-ray data and radio upper limits (Table 1). We further show the posterior light curves for the on-axis jet constraints in Figure 15.

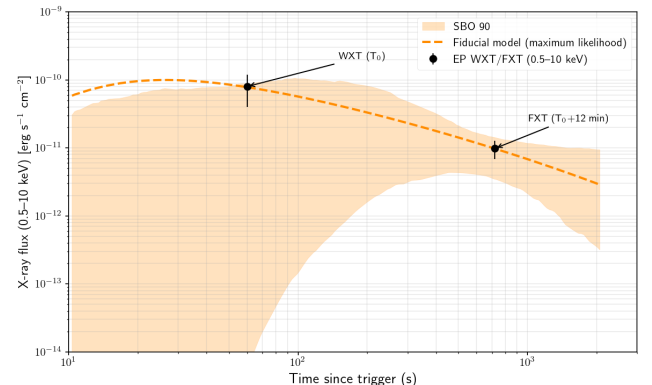


Figure 12. The allowed 90% X-ray light curves for SBO emission from our fit to the EP data (black).

⁴⁰ https://github.com/kryanhinds/subphot_pipe

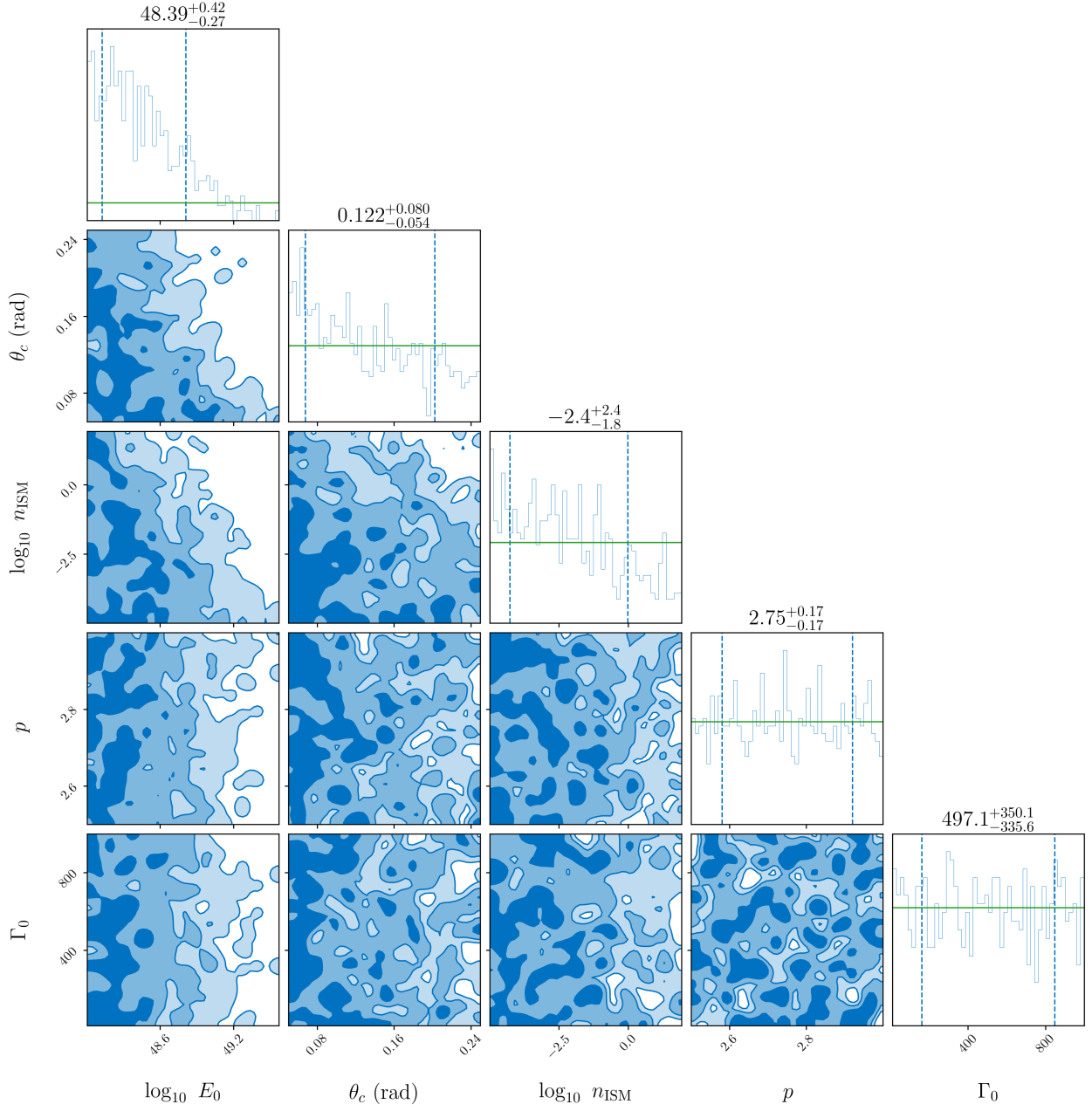


Figure 13. Corner plot showing our constraints on an on-axis jet assuming $\epsilon_e = \epsilon_B = 0.1$. The prior distribution is shown in green, highlighting that our constraint on $E_{K,iso}$ is data-driven rather than prior-driven.

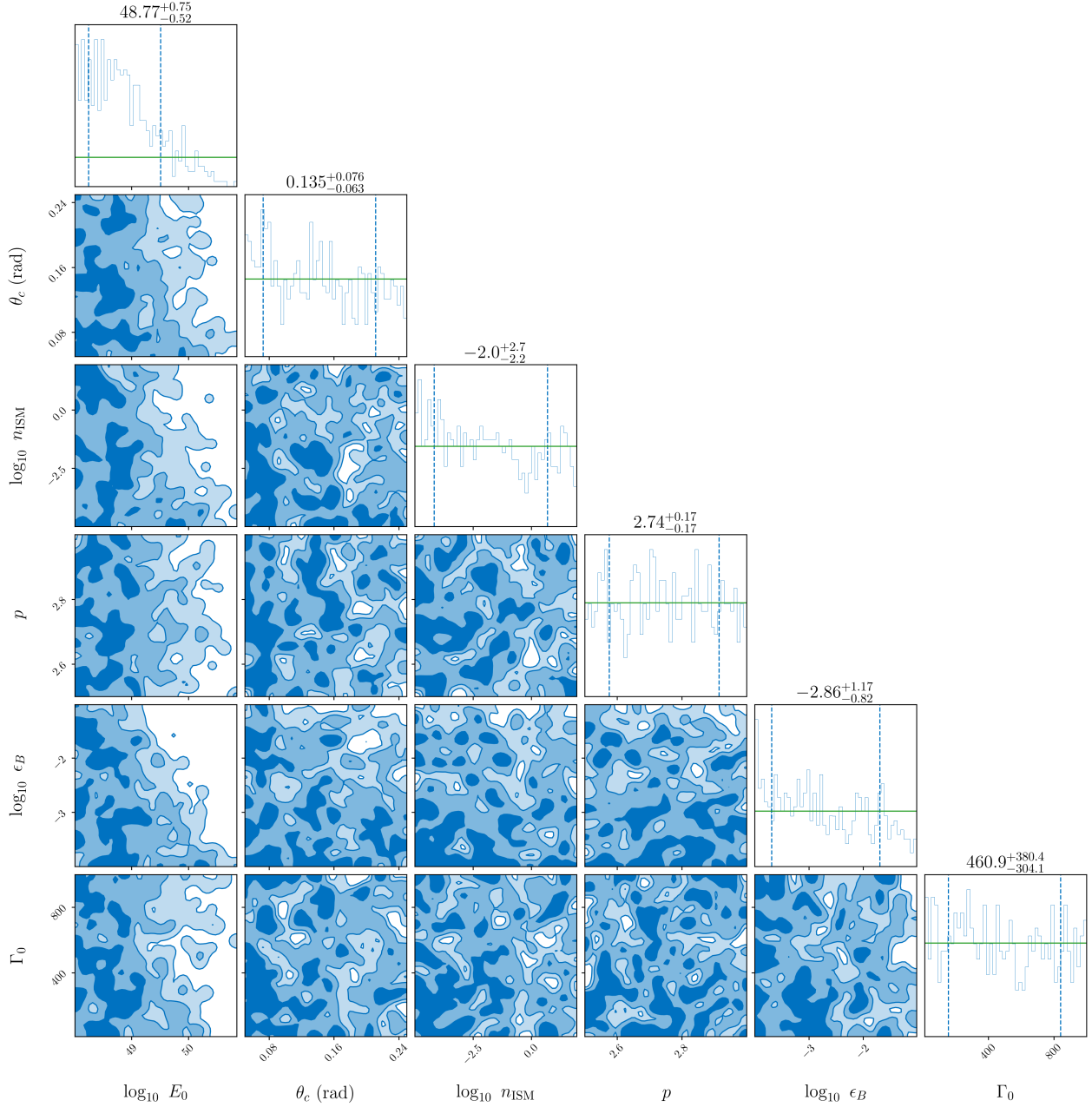


Figure 14. Corner plot showing our constraints on an on-axis jet allowing ϵ_B to vary over the range $10^{-4} \leq \epsilon_B \leq 0.1$. The prior distribution is shown in green, highlighting that our constraint on $E_{K,iso}$ is data-driven rather than prior-driven.

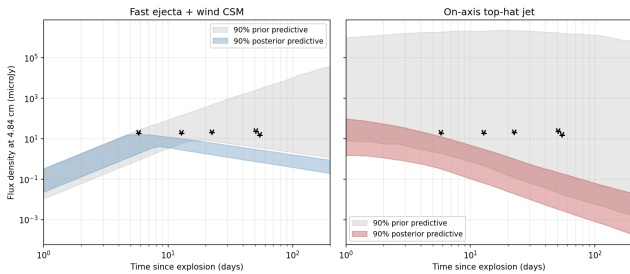


Figure 15. The allowed light curves for synchrotron radio emission from the fastest SN ejecta interacting with the outer, wind-like CSM (color) compared to the full light-curve space probed by our priors. We fix $\epsilon_e = \epsilon_B = 0.1$.

A.4. Host-galaxy SED Fitting

We obtain public photometric observations of the host using FrankenBlast (A. E. Nugent et al. 2026), a customized version of the Blast web application (D. O. Jones et al. 2024) that performs global aperture photometry on transient host galaxies using archival imaging catalogs including: the Galaxy Evolution Explorer (GALEX; A. Y. K. Bouquin et al. 2018), the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS; K. C. Chambers et al. 2016), Dark Energy Camera Legacy Survey Data Release 9 (DECaLS DR9; A. Dey et al. 2019), 2MASS (M. F. Skrutskie et al. 2006), and the Wide-field Infrared Survey Explorer (WISE;

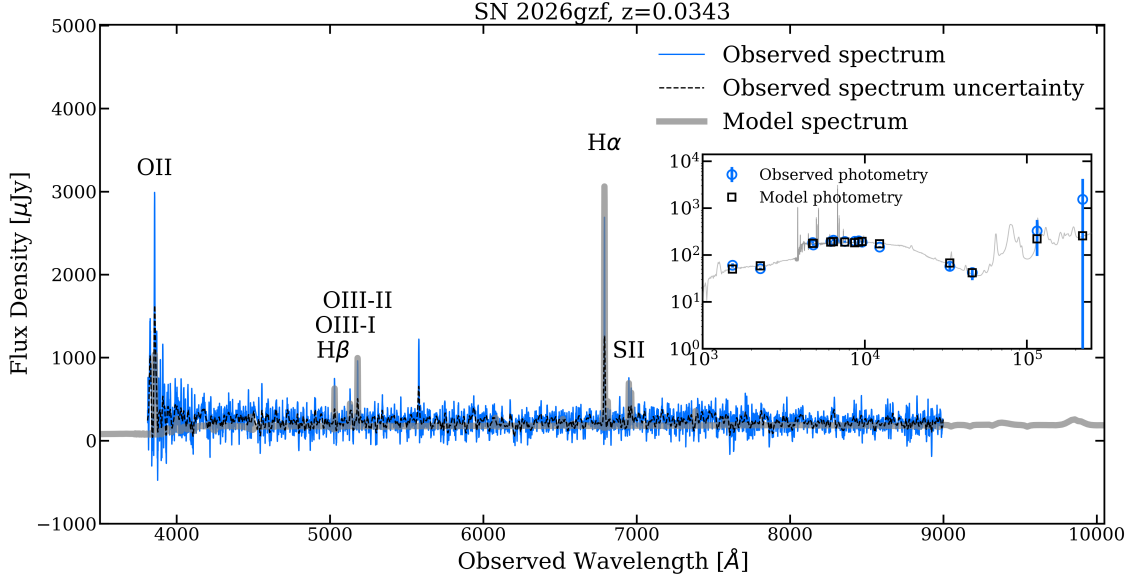


Figure 16. The *Prospector*-determined model spectrum (gray) compared to the DESI-observed spectrum of the host of SN 2026gzf (blue). We highlight high-S/N lines in the observed spectrum. The inset shows the comparison between the model photometry (black squares) and observed photometry (blue circles). We find that *Prospector* fits the observed properties well, suggesting that the derived stellar population properties are accurate.

E. L. Wright et al. 2010). We show the photometry of SDSS J095942.88+002506.2 used in our analysis in Table 3. We refer the reader to A. E. Nugent et al. (2026) for specific details on the FrankenBlast aperture photometry technique. Additionally, we employ a spectrum of the host from the Dark Energy Spectroscopic Instrument (DESI) DR 1 (DESI Collaboration et al. 2026) in our analysis. We observe prominent emission lines in the host spectrum, indicative of recent star formation: [O II] λ 3727, H β , [O III] λ 4959, 5007, H α , and [S II] λ 6717, 6731 at $z = 0.0343$.

To obtain constraints on the global host-galaxy stellar population properties (e.g., stellar mass, SFR), we model the host-galaxy photometry and spectrum with *Prospector* (J. Leja et al. 2019; B. D. Johnson et al. 2021), a Python-based stellar population modeling inference code. We sample stellar population properties using a nested sampling fitting routine, *dynesty* (J. S. Speagle 2020), and build model SEDs with *FSPS* and *python-FSPS* (C. Conroy et al. 2009; C. Conroy & J. E. Gunn 2010). Internally, *Prospector* employs WMAP9 cosmology (G. Hinshaw et al. 2013; C. L. Bennett et al. 2014), MIST models (B. Paxton et al. 2018), and the MILES spectral library (J. Falcón-Barroso et al. 2011). Our *Prospector* model includes the G. Chabrier (2003) initial mass function (IMF), a nebular emission model from N. Byler et al. (2017), and the M. Kriek & C. Conroy (2013) dust attenuation model, which measures an offset from the D. Calzetti et al. (2000) attenuation curve and the amount of light attenuated from young ($\tau_{V,1}$) and old ($\tau_{V,2}$) stars. Given that the host is detected in multiple WISE filters, we also apply the B. T. Draine & A. Li (2007) IR dust emission model, in which we sample the polycyclic aromatic hydrocarbon mass fraction (q_{pah}), and a mid-IR active galactic nucleus (AGN) model, constrained

through the mid-IR optical depth (τ_{AGN}) and total AGN luminosity (f_{AGN} ; a fraction of the total host bolometric luminosity). We sample stellar metallicity (Z_*) and total mass formed in the host (M_F) through the A. Gallazzi et al. (2005) mass–metallicity relation, to ensure that we obtain a physically realistic Z_* , which can often become degenerate with other properties (e.g., dust and age) in SED fitting (C. Conroy 2013). We model the star formation history (SFH) in the host with a seven-bin nonparametric model, where we assume a constant SFR in each bin. The first two bins are spaced from 0 to 30 Myr and 30 to 100 Myr, and the last five bins are log-spaced until the age of the Universe at the redshift of the host.

To fit the host-galaxy spectrum, we model the spectral continuum with a sixth-order Chebyshev polynomial, apply a model to normalize the spectral continuum to the observed photometry, and employ a spectral smoothing model that matches the resolution of the model spectrum to the observed spectrum. We additionally sample a gas-phase metallicity (Z_{gas}) and gas ionization parameter (U_{gas}) to fit the spectral lines. To ensure that the spectrum is not overweighted in the fit in comparison to the photometry, we also include a model to inflate the spectral noise. Finally, we employ a pixel outlier model to marginalize over bad pixels, cosmic rays, and other sources of poorly modeled noise in the spectrum. We show the *Prospector* SED fit (Section 5.1) of the host of SN 2026gzf in Figure 16.

A.5. Photometry Table and SEDm Spectra

We present the photometry shown in Figures 2 and 9 in Table 4. We show the SEDm spectra in Figure 17.

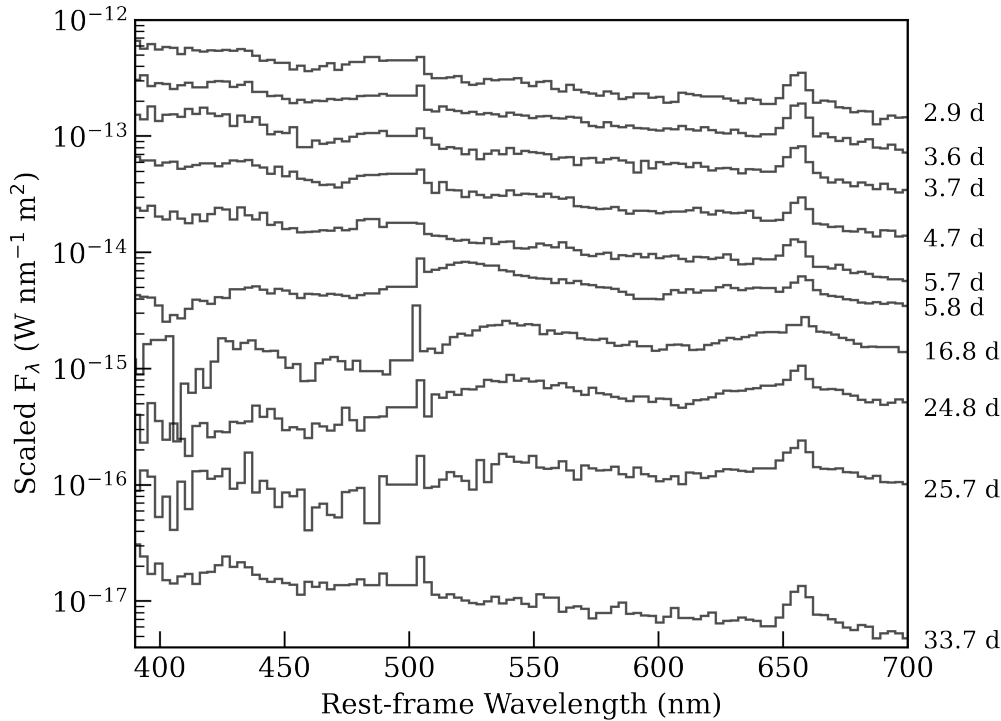


Figure 17. Spectral sequence of EP260321 from SEDM. Some narrow host-galaxy lines are clipped for display purposes, and spectra are binned to 3 nm.

Table 4
Photometric Observations of SN 2026gzf

Date	δt (days)	Instrument	Filter	Magnitude (AB mag)
61121.300	0.779	ZTF	<i>r</i>	19.85 ± 0.18
61121.316	0.795	ZTF	<i>g</i>	19.65 ± 0.10
61122.225	1.704	ZTF	<i>r</i>	18.84 ± 0.04
61122.226	1.705	ZTF	<i>r</i>	18.79 ± 0.09
61123.178	2.657	WINTER	<i>J</i>	18.78 ± 0.11

Notes. Observations are not corrected for Galactic or local extinction. Times are presented in the observer frame.

(This table is available in its entirety in machine-readable form in the [online article](#).)

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